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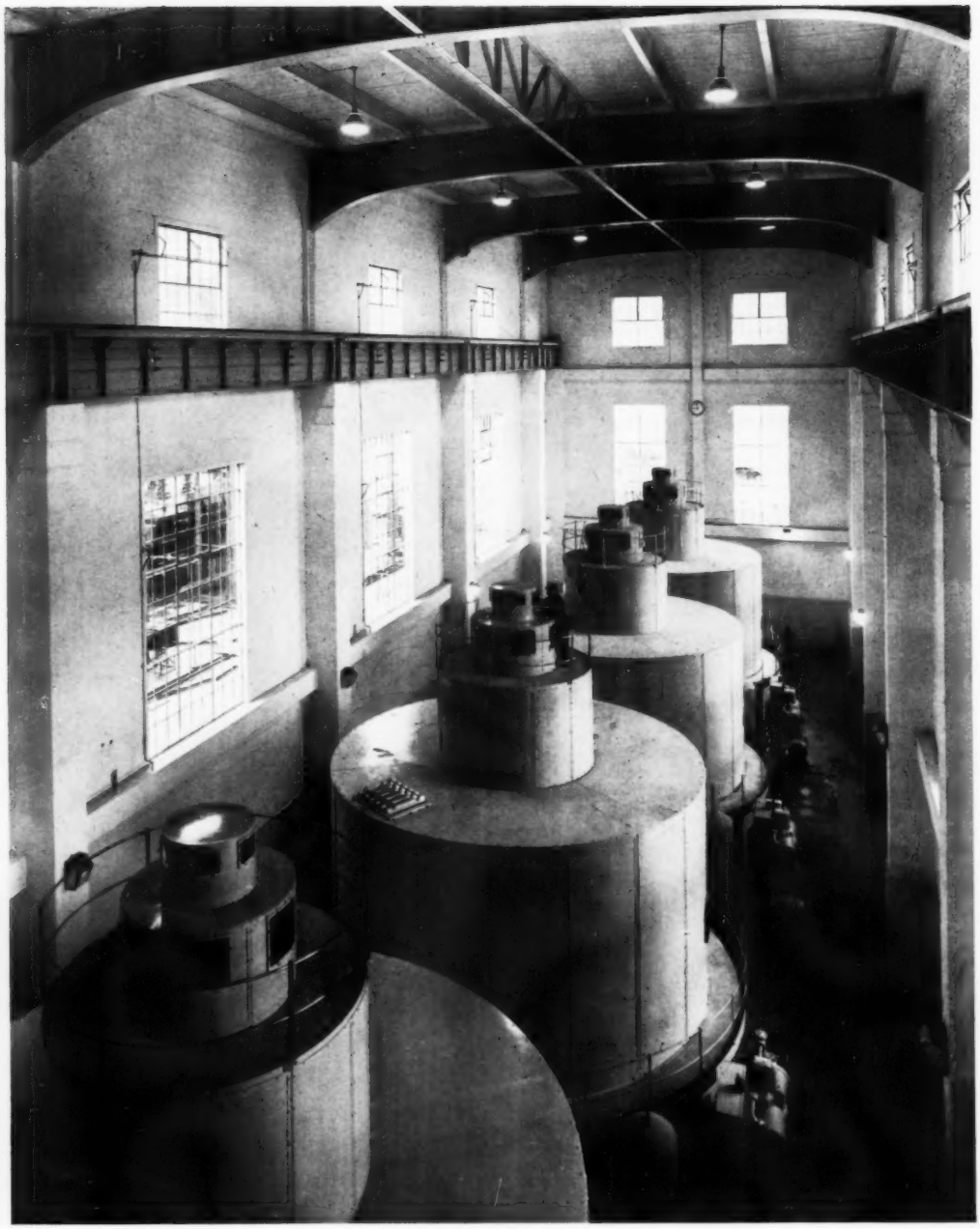


The four 45,500 *h.p. water turbine generating sets in Loch Sloy power station of the North of Scotland Hydro-Electric Board*

Loch Sloy Power Scheme of the North of Scotland Hydro-Electric Board

By J. C. BEVERLEY, M.A., A.M.I.E.E., Hydraulic Section.

THE CHOICE OF Loch Sloy as a source of water supply for the largest hydro-electric station in the British Isles was based on three factors which are fundamental for the production of hydro-electric power in large quantities :—

(i) The rainfall in the area is very heavy.
(ii) The physical layout is exceptionally favourable.
(iii) There is a centre demanding heavy peak electrical load near-by.

It was estimated that the long-term average rainfall over the catchment area would be 115 inches per year, but over the past three years the actual amounts recorded by individual gauges have been as follows :—

Year.	Total Rainfall.
1948	163 inches.
1949	154 ,,
1950	138 ,,

When the full catchment area is in use, every inch of rain will give about 1,000,000 units, and therefore the extra rainfall will result in substantial additional financial gain without any additional capital expenditure.

Loch Sloy itself was quite small having a natural length of under 1 mile and a width of only a few hundred yards ; also its catchment area was only 6½ square miles. However, its location only 2 miles from Loch Lomond and 760 ft above its level gives the water there great potential value, and there was a suitable site for the power station on the banks of Loch Lomond at a convenient point. In addition, the steep sided valley in which Loch Sloy lies and the rock formation at the river outlet from the loch gave good conditions for building a high dam.

Heavy rainfall and a satisfactory physical layout are not sufficient to justify building a generating station if the power cannot be used effectively, but Loch Sloy is only 40 miles from Glasgow with its heavy industrial load and short-time peak power demands.

PREVIOUS SCHEMES

The advantages of the site were first considered in 1906 and various proposals have been investigated since then, the major efforts before the present development being in 1936 and 1937.

The 1937 scheme involved over 200,000 kW of plant in 5 or 6 sets of 45 or 40 MW each, which is considerably larger than the scheme finally adopted. These sets would have been horizontal and some of them would have been arranged with a pump connected to the alternator shaft at the opposite end to the turbine. These pumps were to be of 20,000 or 25,000 kW capacity and would have been driven by the alternators working as synchronous motors, to raise water from Loch Lomond back to Loch Sloy during times of low load on the system. The water would then have been returned through the turbines during peak periods to augment the power from Loch Sloy's catchment area. With this arrangement a greater installed plant capacity was economical although the net number of units generated would be no greater.

An earlier scheme was even larger and would have had an eventual capacity of 360,000 kW with 100,000 kW of pumps, but these schemes did not proceed due to opposition from other interests even though the cost per kW was lower than for a comparable steam station.

The overall efficiency of a pumped storage scheme is comparatively low, about 60 per cent, which means that for every 60 kWh generated during the peak load period, 100 kWh must be expended in pumping water up to the reservoir by night, the extra 40 units being required to overcome losses in turbines, pumps, alternators and tunnel. This difference of 40 kWh per cent represents a continuous charge against a reversible pumping scheme, which must be offset, if the scheme is to pay, by the value of the kilowatts of peak load produced.

It is of particular interest that the 40 per cent in question represents a consumption of coal *above* that which would be consumed by a new steam station. A reversible pumping scheme therefore contributes less than nothing to the conservation of coal resources, and its merits are confined to providing the most economical form of peak load power generation.

The criterion therefore by which a reversible pumping plant must be judged is whether the generating costs, including interest on capital and sinking fund, plus the cost of power used for pumping, amount to appreciably less than the cost of producing peak load from a modern steam station. If this is so, then there is a prima facie case for carrying out a pumping scheme.

It is an interesting comment on these pumping schemes which were rejected, that consideration is now being given to the addition of pumping to the present Loch Sloy scheme. The layout of civil works would have been mainly very similar to that which has been adopted.

PRESENT SCHEME

Construction Scheme

When the North of Scotland Hydro-Electric Board was formed in 1943 under the Hydro-Electric Development (Scotland) Act, the first scheme to be promoted was that at Loch Sloy. The Construction Scheme was approved by the Electricity Commissioners in June 1944, and confirmed by the Secretary of State for Scotland in May 1945. It provided for 130,000 kW of generating plant supplied from Loch Sloy, and two small hydro-electric stations at Morar and Lochalsh on the west coast of Scotland which, although not

Fig. 1. *The dam from the downstream side*

connected either hydraulically or electrically with Loch Sloy, are uneconomical local supply schemes partly financed by the profit from the sale of power from Loch Sloy.

The general layout of the scheme finally adopted is very similar to earlier proposals put forward by The English Electric Company, with the exception that no provision is made for pumping water from Loch Lomond to Loch Sloy and accordingly the sets have been arranged with vertical shafts.

The generating plant at Loch Sloy comprises four 45,500 b.h.p. reaction type turbines operating at 428 r.p.m. under a net head of 810 ft, driving 32.5 MW 11 kV 3-phase 50 cycles alternators.

Catchment Area

The natural catchment area is being increased by 4½ times to 27½ square miles by trapping head waters of rivers and streams which previously ran direct into Loch Lomond, and also some which ran into River Fyne on the west. These diversions are made possible by the high level of the surrounding ground (the summits of Ben Vorlich and Ben Vane are both over 3,000 ft), the water being collected and conveyed either in open aqueducts or subsidiary tunnels. One small diversion has also been made direct into the tunnel through the surge shaft.

A further increase of 4 square miles is to be added to the catchment area, under an additional Construction Scheme, by the trapping of three streams in the south which previously ran into Loch Long.

At present the catchment area is about 19 square miles but further work is being carried on to complete the full area.

The Dam

As already stated, Loch Sloy is insignificant in size and its natural storage capacity is inadequate. To increase its storage a dam 1,160 ft long by 160 ft high has been built across the outlet from the loch, and this has also given a greater head at the turbines. The centre 900 ft section of the dam (Fig. 1) is of the buttress type, and the two end sections which have a maximum height of only 80 ft are of the gravity type. A spillway in two

Fig. 2. Gap between sections of the dam during construction

sections is also included, constructed from pre-cast reinforced concrete beams fixed between adjacent buttresses.

The spoil from the tunnel was unfortunately unsuitable for use as aggregate for concrete, and a quarry was accordingly opened 2 miles from the dam site for the supply of this material. Due to the difficult road access and the severe weather conditions round Loch Sloy, a conveyor belt was built from the quarry to the dam for transport of the material, and this dealt with 200 tons per hour. A total of 400,000 tons of aggregate was required.

The sand was brought from a quarry at Balloch at the South end of Loch Lomond by barge, unloaded at a jetty near the power station site and taken by lorry up to the dam. At the dam, a batching plant for mixing the concrete was erected and the concrete was lifted into position by two overhead cableways each with a span of 1,350 ft.

The two fixed terminal towers and the control point were situated on the left bank of the loch and the two towers on the right bank were movable, which permitted the material to be dumped where required on the dam. The skips each contained 4 cubic yards of material weighing about 7 tons, and the average amount of concrete placed per day was 800 tons.

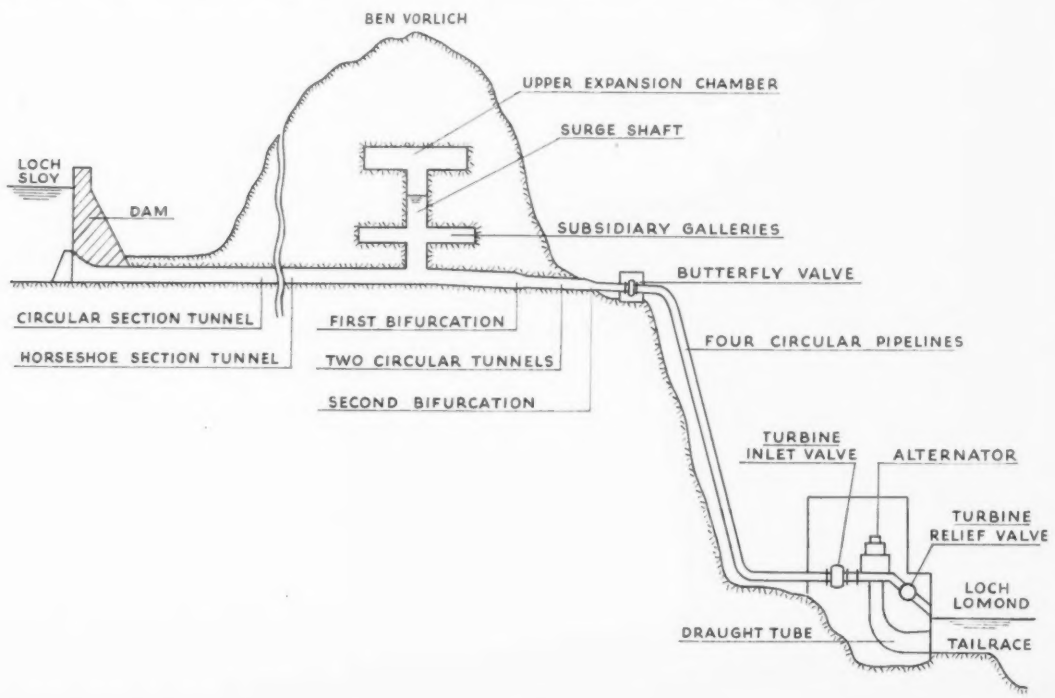
Because of the contraction which takes place when concrete sets, the dam was built in sections, each buttress forming a separate section, and the upstream part of each buttress was constructed several lifts in advance of the stem. The gap between the sections (Fig. 2) was 6 ft wide, and these gaps were closed at least three months after placing the concrete in the buttresses.

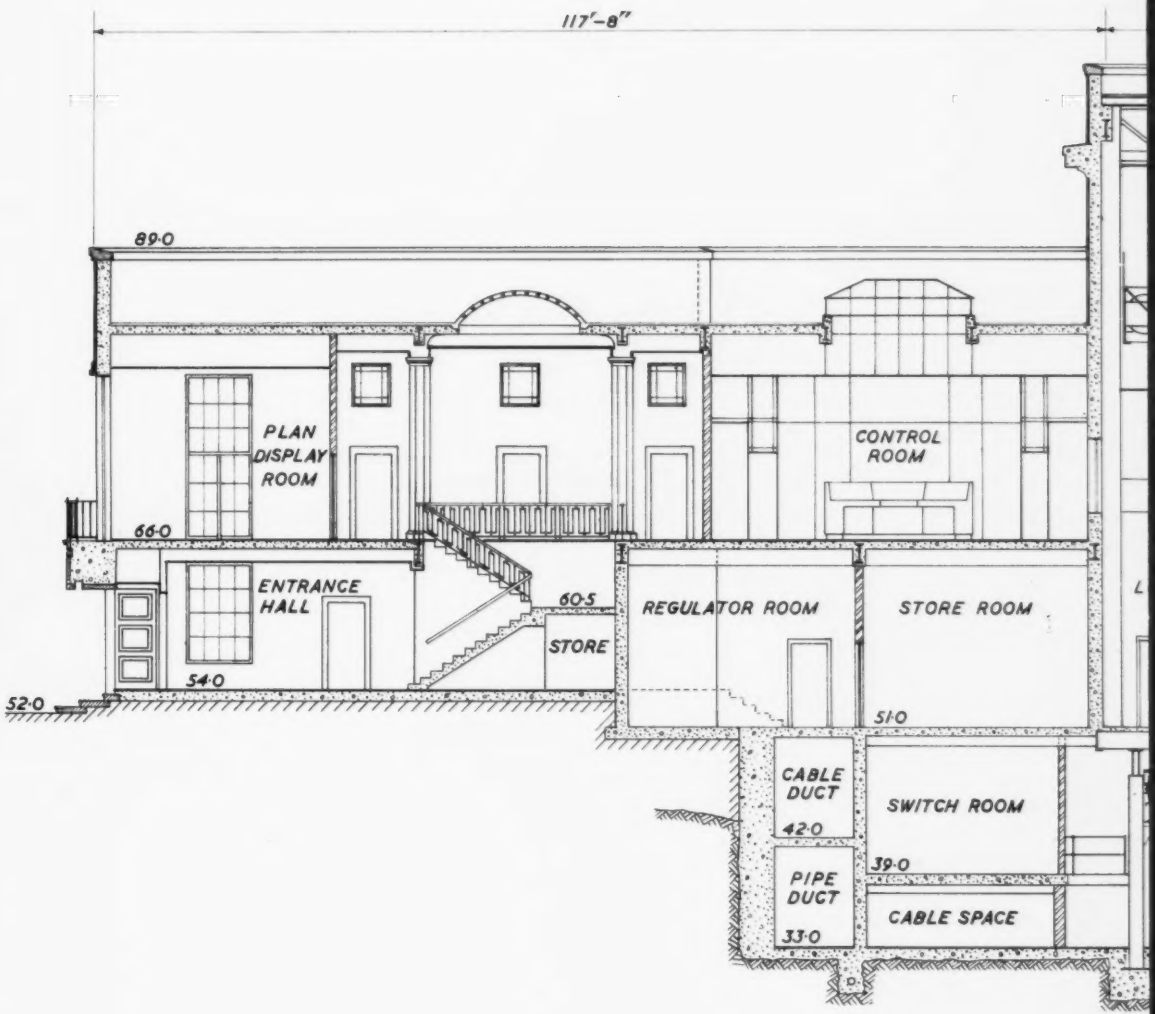
Water from the loch passed through a temporary opening in the dam until the work was sufficiently far advanced, when the gap was closed by a timber stop gate on the upstream side and the space was then permanently plugged, after which filling of the reservoir proceeded.

Screens and Gates

The flow of water to the tunnel from the reservoir is through the base of the intake tower situated in the dam, as seen in Fig. 1. A fixed coarse screen with 6 in. spacing between bars, and a movable fine screen with 3 in. spacing, are located at the intake, and behind the screens is the emergency guard gate. This gate consists of a number of $16\frac{1}{4}$ in. diameter horizontal steel rollers with small brass tubes between each on the upstream side, so arranged that the water pressure forces them into the spaces between the large rollers, making the gate reasonably water tight. The gate is arranged so that it can close automatically under gravity at a speed of 20 ft/min. in an emergency, but opening is by a hoist located at the top of the intake chamber. It can also be used when it is necessary to de-water the main gate chamber which is immediately downstream of it, for maintenance of the main control gate. This main gate is of the counterbalanced type and is normally under water at all times.

Fig. 3. Diagrammatic section, showing dam, pipelines and power house. (Not to Scale)





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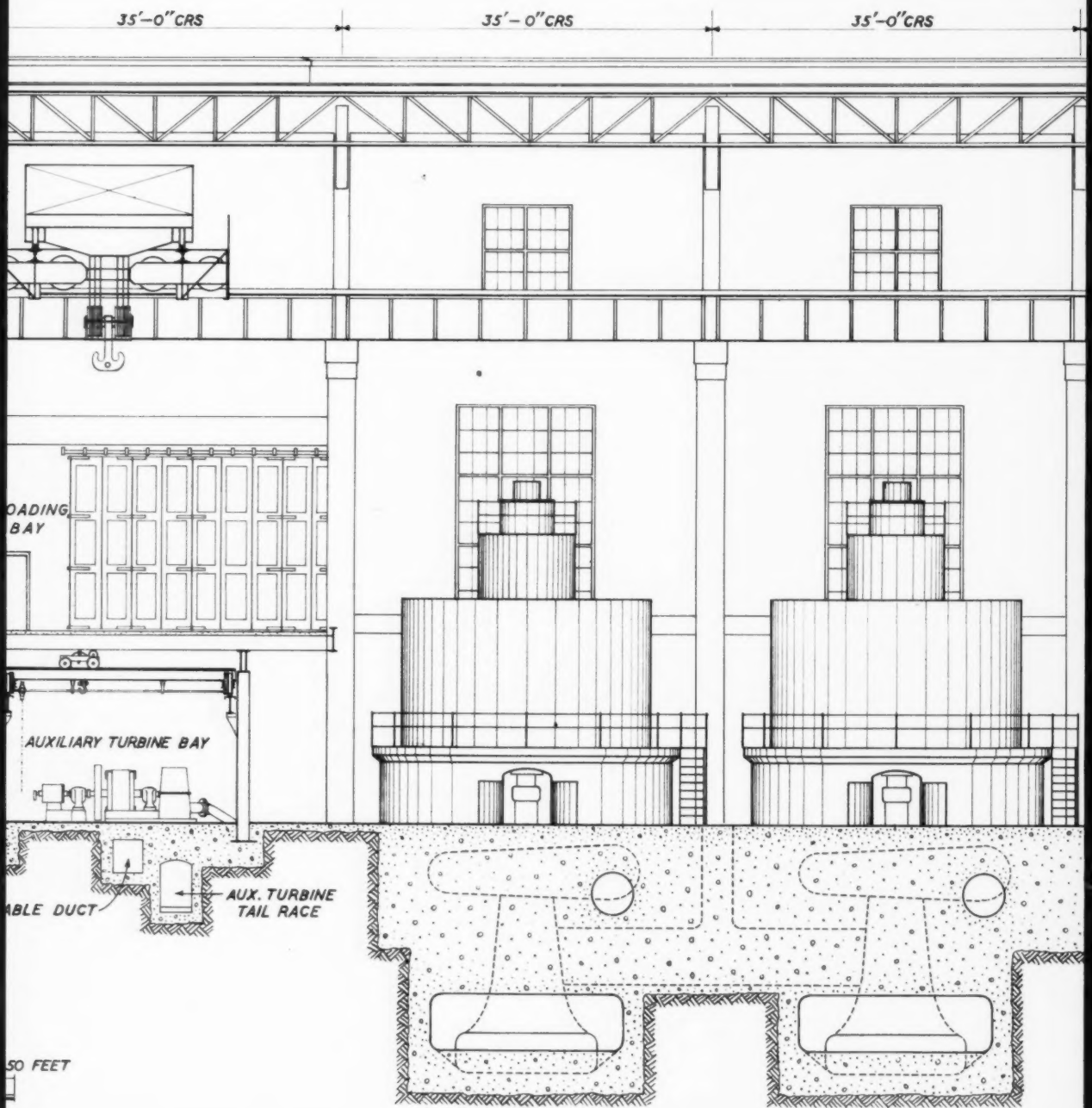
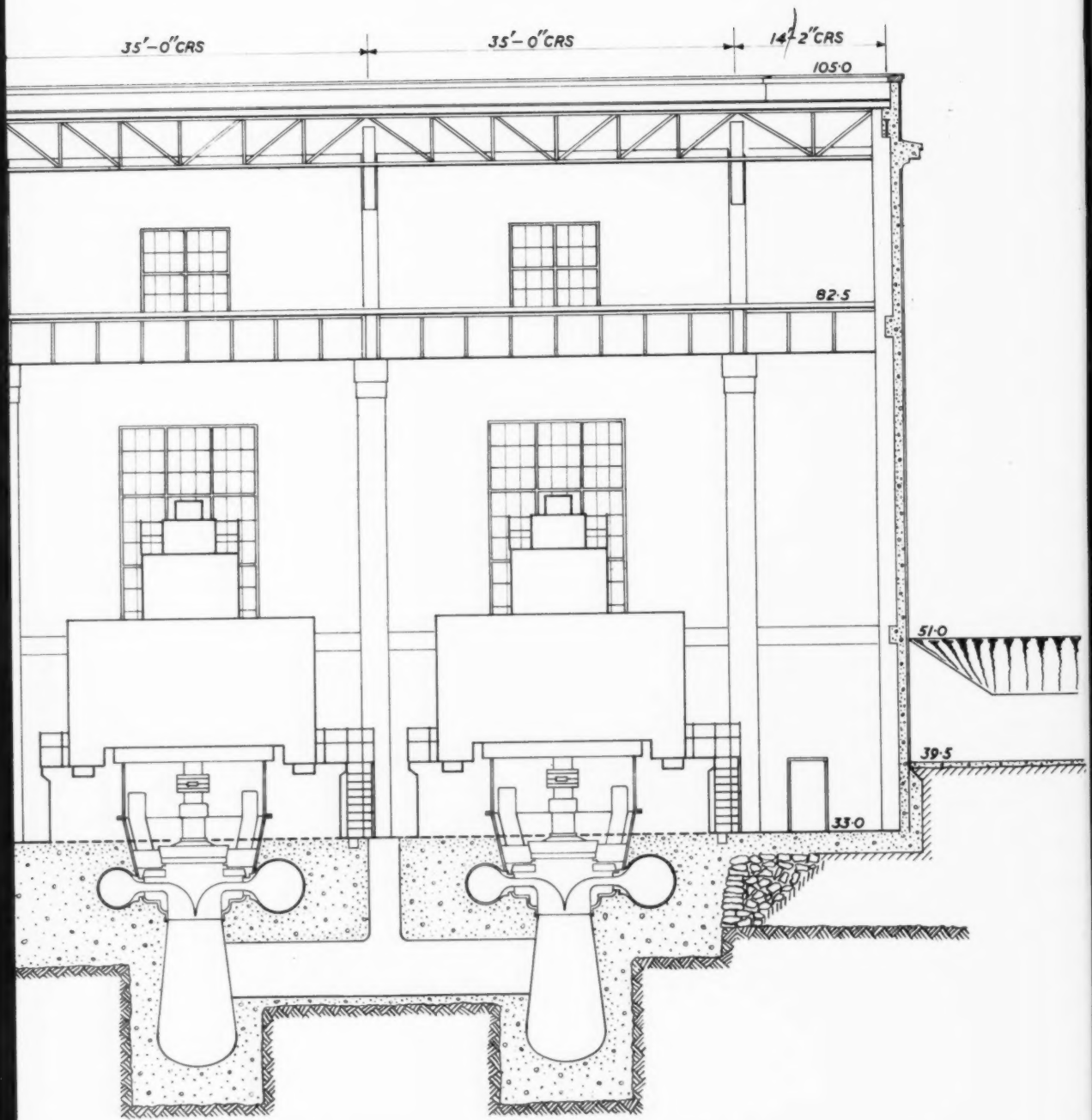
FEET 5 0 5 10 15 20 25 30 35 40 45

PLATE I **General arrangement of the power house**

(By courtesy of Messrs. James Williamson and Partners, Civil Consulting Engineers)




35'-0"CRS
35'-0"CRS
14'-2"CRS
105·0
82·5
51·0
39·5
33·0

Tunnels

Fig. 3 shows a diagrammatic section of the dam, tunnels, pipelines and power house.

From the intake there is a short length of circular steel-lined tunnel 13 ft 6 in. diameter and 750 ft long, with a double bend to connect with the line of the main tunnel which is driven through Ben Vorlich.

The main portion of the tunnel is concrete lined, 8,200 ft long (1½ miles) and of inverted horseshoe section with an equivalent diameter of approximately 16 ft. The tunnel was driven through rock (mica schist) by blasting, and the spoil was removed by diesel and electric locomotives hauling trucks along a temporary narrow gauge track. The main work was carried out from three faces, one at the downstream end from the point where the tunnel emerges on the banks of Loch Lomond, and two in opposite directions from an extra adit driven some distance from the dam at right angles to the main tunnel. A fourth face was also used for a short length of tunnel adjacent to the dam.

The average rate of progress in the tunnel was about 64 ft per week and the maximum reached was 103 ft. During tunnelling, a severe fault was met and a diversion of the tunnel had to be made. The concrete lining was reinforced where necessary, and in parts where loose rock was encountered the reinforcing was made up of steel joists which were left embedded in the lining.

Surge Shaft

About 1,000 ft from the outlet of the tunnel there is a vertical surge shaft, 26 ft diameter and 200 ft high, cut in the rock. This shaft is to control and stabilise pressure surges which occur when the load on the generating sets varies. When load is thrown off, the water supply to the turbines is reduced, which causes a rise in level in the surge shaft. To cover the extreme case of full load being thrown off all four sets, as would occur if the switchgear bus-zone protection tripped in both zones, an expansion chamber 38 ft by 90 ft is provided at the top of the surge shaft. This is to avoid any danger of spilling. A small subsidiary stream is brought into this chamber by means of a branch tunnel.

To cater for load being suddenly thrown on the sets (e.g., when two sets are on light load with minimum water level in the shaft), in which case the level in the surge shaft will go down due to acceleration of the water, and to avoid any possibility of air being drawn in, two subsidiary horizontal galleries are connected to the surge shaft a short distance above the point where it enters the main tunnel. Each gallery is of approximately the same size as the main tunnel (16 ft equivalent diameter) and 120 ft long.

Valve House

Five hundred feet beyond the surge shaft, the horseshoe tunnel divides into the two circular steel lined tunnels each about 500 ft long and 10 ft diameter. These each divide into two 7 ft steel pipes immediately they emerge from the hillside, making four pipes in all which are encased in concrete. Shortly after the two bifurcations there is a 7 ft diameter hydraulically operated butterfly valve in each pipe. These valves are normally operated locally when required but usually they are left open.

To open a valve it is first necessary to balance the water pressure on both sides, and to accomplish this a 10 in. diameter by-pass is provided, with a hand-operated sluice valve through which the pipeline can be gradually filled. When the pipeline is full and the pressure on both sides of the valve is equal, the main butterfly valve is opened by an oil operated servo-motor controlled by solenoids, and the by-pass is then closed.

Closing of the valve can be effected by a push button in the valve house which operates the solenoid controlling the oil servo-motor. In an emergency the valve can also be closed by push button from the power station control room, or if the pipeline fails causing excessive flow a mechanical paddle will close the valve.

Oil pressure for operation is obtained from A.C. motor-driven pumps and is stored in an air/oil pressure receiver in the valve house.

Pipelines and Power House

The four pipelines from the valve house to the power house on the banks of Loch Lomond are 7 ft diameter at the top, tapering in stages to

Fig. 4. Loch Sloy power station, with pipelines and valve house

6 ft 4 in. at the power house where the thickness of the pipeline is $1\frac{9}{16}$ in. The total length of each pipeline is 1,500 ft and it was assembled at site from 24 ft lengths welded and tested at the works. The site joints were all riveted.

Four anchor blocks are provided ; one can be seen in Fig. 4 built into the valve house wall, two are on the hillside, and the last is behind the power house and this also forms the foundations for the transformers. At the upstream end of each pipeline before each anchor block there is an expansion joint to allow for temperature changes.

Turbine Inlet Valves

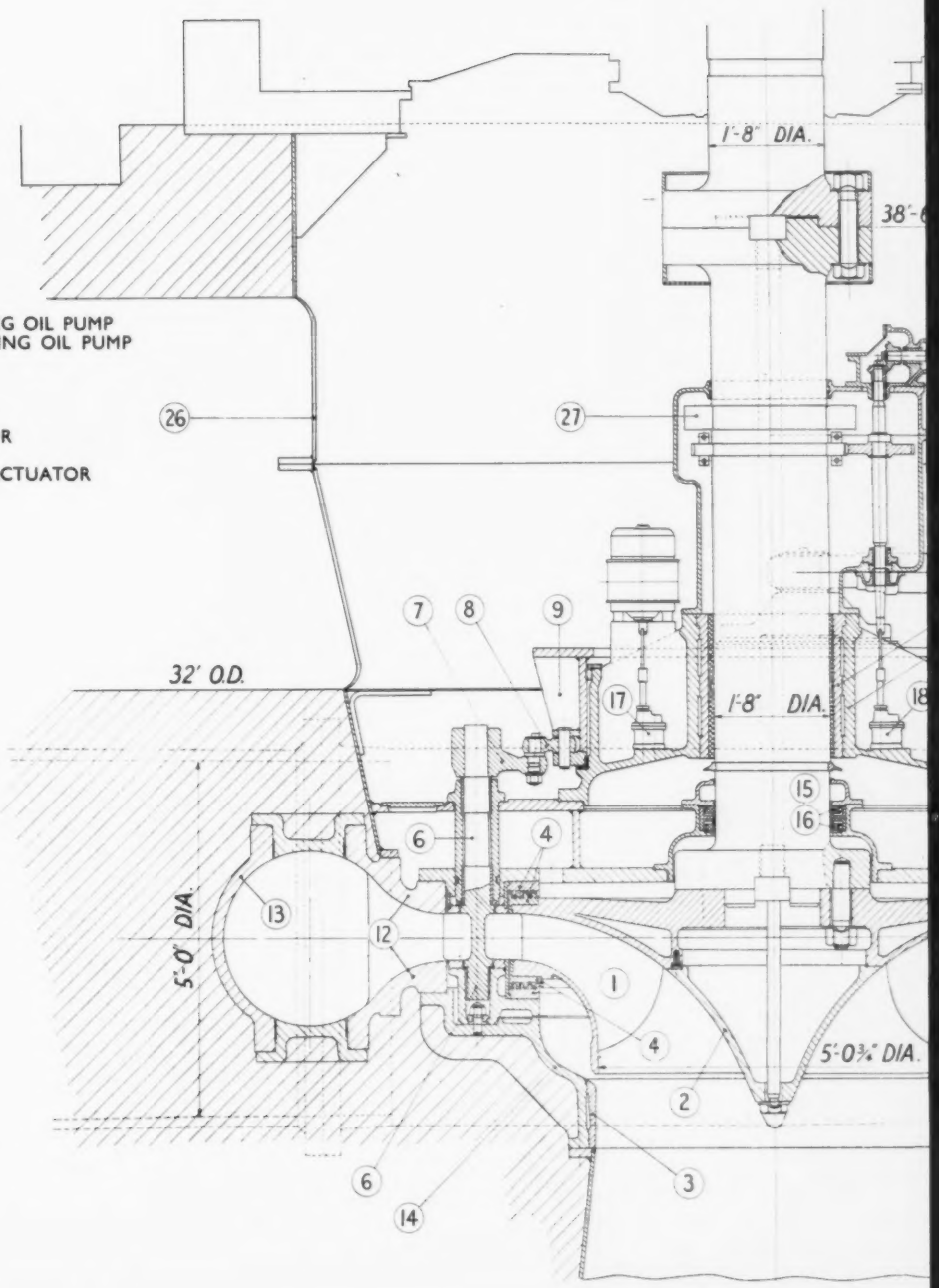
Each pipeline is connected to the turbine through a 6 ft 4 in. diameter "English Electric" cylindrical balanced valve which is a type much used in hydro-electric stations for a number of years. The maximum static water head on the valve is 920 ft, equivalent to a pressure of approximately 400 lb/sq. in. and the valve is designed to operate against this full unbalanced pressure when priming the spiral casing. Unlike the pipeline valves no by-pass is fitted. The valve also has to close against full flow if necessary.

The closing member of the valve consists of a cylinder which seals against an inner body inside the valve and fixed to the outer body by ribs. The upstream nose of the inner body and some of the ribs can be seen in Fig. 5. The closing force on the cylinder is obtained from pipeline water pressure on the back end of the cylinder, admitted through a control valve. To guard against too rapid closure at the end of the stroke, which would set up excessive water hammer, a control screw which travels with the valve cylinder reduces the supply of water and so progressively diminishes the speed of closing. Opening of the valve is effected by releasing the water pressure on the closing side of the cylinder which is then opened by the pipeline pressure. The control valve is operated by a lever for manual opening of the valve, but closing can be carried out electrically in an emergency.

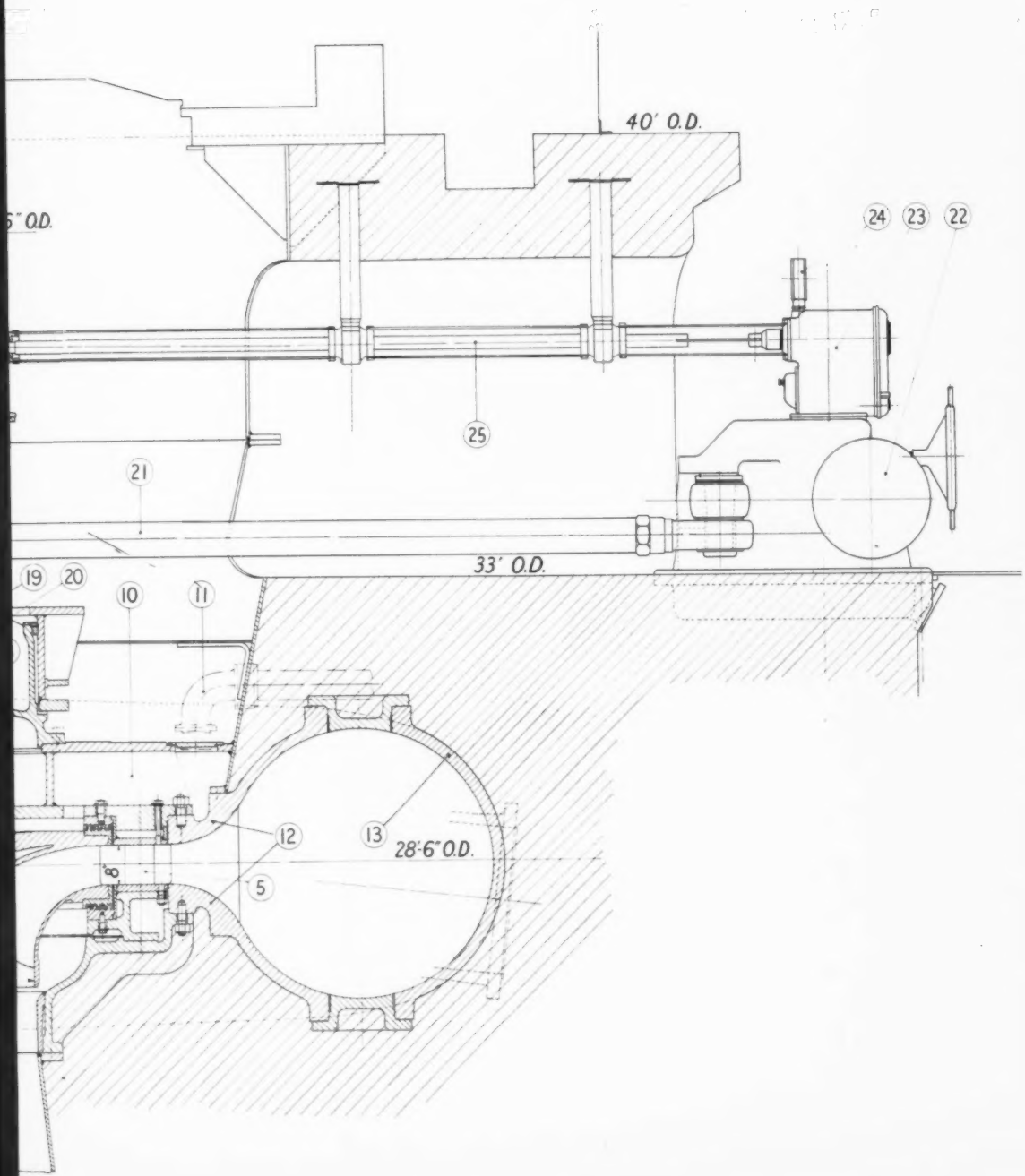
The connection of the upstream flange of the valve to the downstream flange of the pipeline

PLATE II **Sectional elevation of 45,500 h.**

Ref. No.	Description
1	STAINLESS STEEL RUNNER
2	RUNNER COVER
3	STAINLESS STEEL THROAT RING
4	SEALING RINGS
5	GUIDE VANES
6	GUIDE VANE TRUNNIONS
7	REGULATING LEVERS
8	BREAKING LINKS
9	REGULATING RING
10	TOP COVER
11	BALANCING PIPES
12	SPEED RING
13	CAST STEEL SPIRAL CASING
14	FOUNDATION RING
15	TURBINE SHAFT
16	SHAFT GLAND CARBON RINGS
17	ELECTRICALLY DRIVEN LUBRICATING OIL PUMP
18	MECHANICALLY DRIVEN LUBRICATING OIL PUMP
19	TURBINE BEARING
20	TURBINE BEARING HOUSING
21	MAIN REGULATING RODS
22	OIL PRESSURE SERVO-MOTOR
23	AUTOMATIC GOVERNOR ACTUATOR
24	GOVERNOR TACHOMETER
25	DRIVING SHAFT FOR GOVERNOR ACTUATOR
26	GENERATOR SUPPORT
27	OVERSPEED PENDULUM



p. water turbine at Loch Sloy



introduced a difficult problem as under the high head and with the large diameter any flexible coupling was not considered to be satisfactory. Closing of the final joint was actually carried out in the following manner. The downstream flange of the pipeline was left undrilled and 2 in. short of the calculated position of the mating flange of the valve. The valve was positioned, the gap accurately measured and a ring then made to these dimensions. Meanwhile the pipeline flange was drilled through the bolt holes in the valve flange. Finally the ring was dropped in position and bolted up.

Turbines

After passing through the valve the water enters the spiral casing of the vertical shaft reaction turbine. The spiral with its speed ring and stay vanes was cast in one piece and the finished weight of the casting was over 30 tons. At site the spiral is completely embedded in concrete.

A branch on the downstream side of the spiral casing is provided for connection to the relief valve which operates automatically in synchronism with the governor when load is thrown off the turbine, and so limits the pressure rise. The valve is of the same type as the turbine inlet valve.

The regulating gear is of orthodox design ; there are 24 forged steel guide vanes which control the flow of water to the runner, and these when closed cut off the supply of water to the turbine runner. The guide vanes are connected outside the spiral casing to a regulating ring through cast iron breaking links which give protection against damage if an obstruction becomes lodged between any of these vanes. The regulating ring is rotated to adjust the position of the guide vanes for load control, by substantial connecting rods operated by an oil pressure servo-motor.

In the top cover is mounted a carbon ring gland round the main shaft to prevent water passing from above the turbine runner up the shaft. The turbine shaft bearing is carried on the top cover as well as its oil sump. The bearing has forced lubrication obtained from a gear-driven pump, with a D.C. motor-driven pump as standby which is automatically controlled to cover starting up and shutting down periods when the gear pump is not delivering sufficient oil. The governor head in the actuator which controls the governor servo-motor is also gear driven from the main shaft.

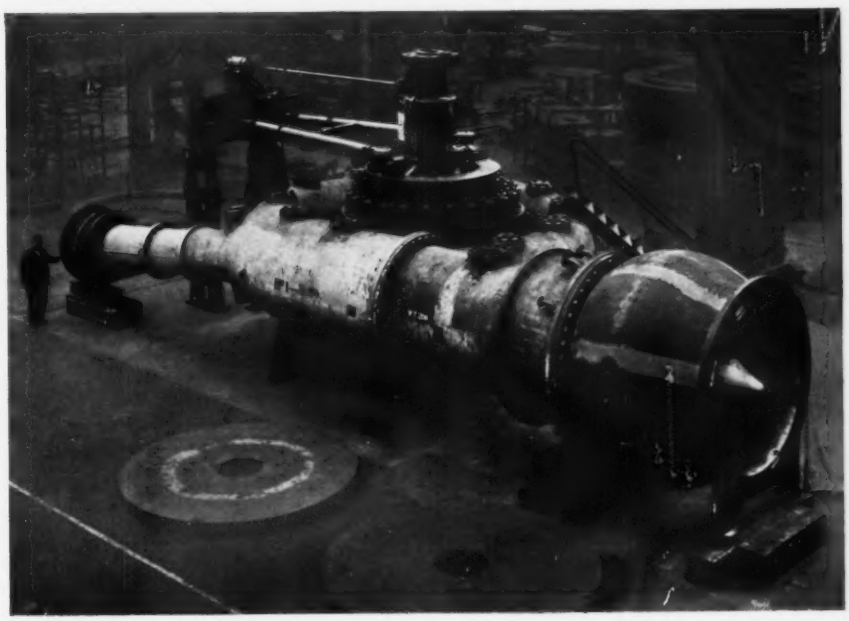


Fig. 5. Assembly of turbine for Loch Sloy, with the inlet and relief valves, at the Glasgow Works of Messrs. Harland and Wolff, Ltd., sub-contractors to The English Electric Company

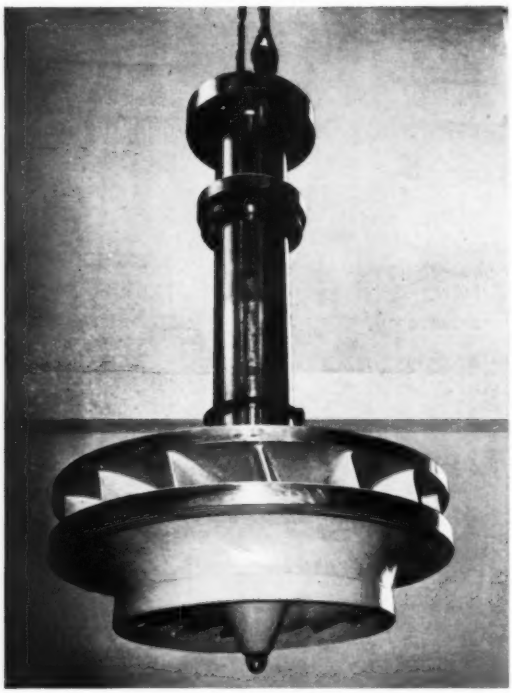


Fig. 6 Runner and shaft for 45,500 h.p. water turbine

The turbine shaft is solidly coupled to the alternator shaft above, and the torque is transmitted by transverse fitted keys which eliminate the use of fitted bolts.

The turbine runner (Fig. 6) is of interesting construction. Because of the high head the passages through the runner are very small (about 2 in. minimum) and it would have been very difficult to cast a runner with passages of sufficient accuracy or with a smooth enough finish without appreciable hand grinding. The complete runner was accordingly fabricated from steel and stainless steel plates and castings. Briefly, the method of assembling the runner was as follows :—

(i) Cast stainless steel vanes ground smooth were assembled and welded to the stainless steel crown and rim. Thus all the water passages are of stainless steel. The ingenious welding sequence developed allowed good access to every weld as it was made.

(ii) A cast steel crown disc was then welded over the crown. This disc gives great strength to the wheel and carries the torque to the shaft. At the same time a considerable weight of stainless steel is saved.

(iii) The sealing rings were shrunk on.

(iv) The complete runner was finally machined and balanced.

The sealing rings which separate the high pressure water side of the runner from the top and bottom of the runner which are at exhaust pressure, are of the multi-labyrinth type with radial clearances of approximately .030 in. on a diameter of over 7 ft.

The design of the runner was proved by test on an $\frac{1}{8}$th scale model of the complete turbine. Accurate tests were then carried out at The English Electric Company's hydraulic laboratory at Rugby. The actual rating of the turbine is 45,500 b.h.p. at 810 ft net head and it runs at 428 r.p.m. The head range is 880 to 720 ft net.

Alternators

The 11 kV vertical direct-coupled alternators are each rated at 32,500 kW 0.95 p.f. (34,210 kVA) 428 r.p.m., and they are also suitable for generation at 27,500 kW 0.8 p.f. (34,375 kVA), although usually the power factor is nearly unity or even leading.

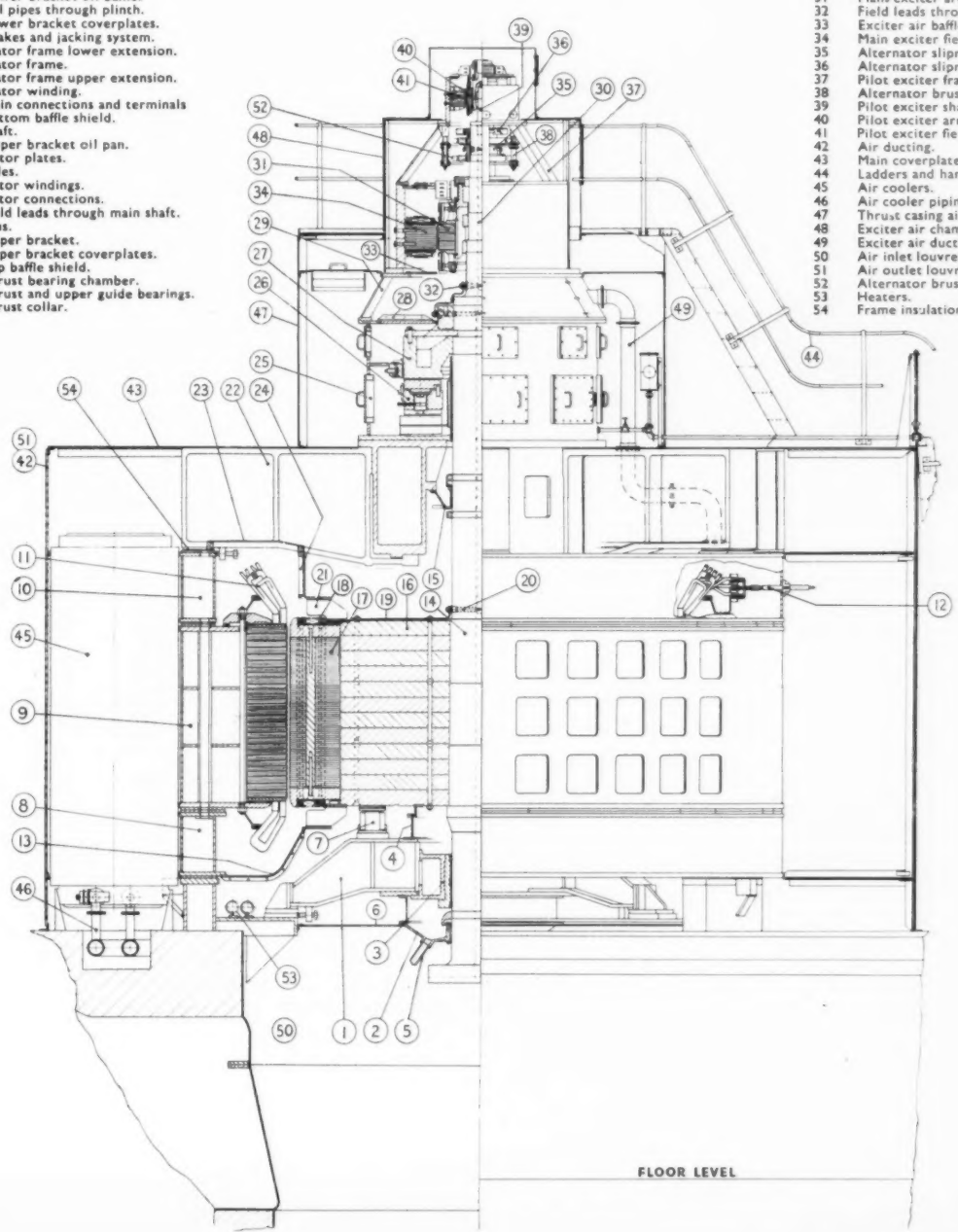
The stator, which was transported in halves, is carried on a fabricated steel support which is bolted to the turbine speed ring and encased in concrete. The winding is of the two-layer basket type of conventional design.

In common with other water turbine driven alternators, the rotor (Fig. 7) was required to be heavy to give a high flywheel effect, and had also to be designed to withstand prolonged running at the maximum runaway speed of the turbine which could occur if the turbine gates were held open with no electrical load on the machine. This speed was 793 r.p.m. and one alternator was tested under this condition in the Stafford Works. To meet these requirements, the rotor was constructed of twelve steel plates each $5\frac{1}{4}$ in. thick which were shrunk and keyed to the shaft in three packets of four plates

PLATE III **Cross-sectional view of 32,500 kW alternator with direct-coupled main and pilot exciters**

Ref. No.	Description
1	Lower bracket
2	Lower bracket oil pan.
3	Lower guide bearing.
4	Lower bracket oil baffle.
5	Oil pipes through plinth.
6	Lower bracket coverplates.
7	Brakes and jacking system.
8	Stator frame lower extension.
9	Stator frame.
10	Stator frame upper extension.
11	Stator winding.
12	Main connections and terminals
13	Bottom baffle shield.
14	Shaft.
15	Upper bracket oil pan.
16	Rotor plates.
17	Poles.
18	Rotor windings.
19	Rotor connections.
20	Field leads through main shaft.
21	Fans.
22	Upper bracket.
23	Upper bracket coverplates.
24	Top baffle shield.
25	Thrust bearing chamber.
26	Thrust and upper guide bearings.
27	Thrust collar.

Ref. No.	Description
28	Oil baffle.
29	Main exciter support.
30	Main exciter shaft.
31	Main exciter armature.
32	Field leads through exciter shaft.
33	Exciter air baffle.
34	Main exciter field.
35	Alternator sliprings.
36	Alternator slipring fan.
37	Pilot exciter frame support.
38	Alternator brushgear.
39	Pilot exciter shaft extension.
40	Pilot exciter armature.
41	Pilot exciter field.
42	Air ducting.
43	Main coverplates.
44	Ladders and handrails.
45	Air coolers.
46	Air cooler piping.
47	Thrust casing air chamber.
48	Exciter air chamber.
49	Exciter air duct.
50	Air inlet louvres and filters.
51	Air outlet louvres.
52	Alternator brush.
53	Heaters.
54	Frame insulation.



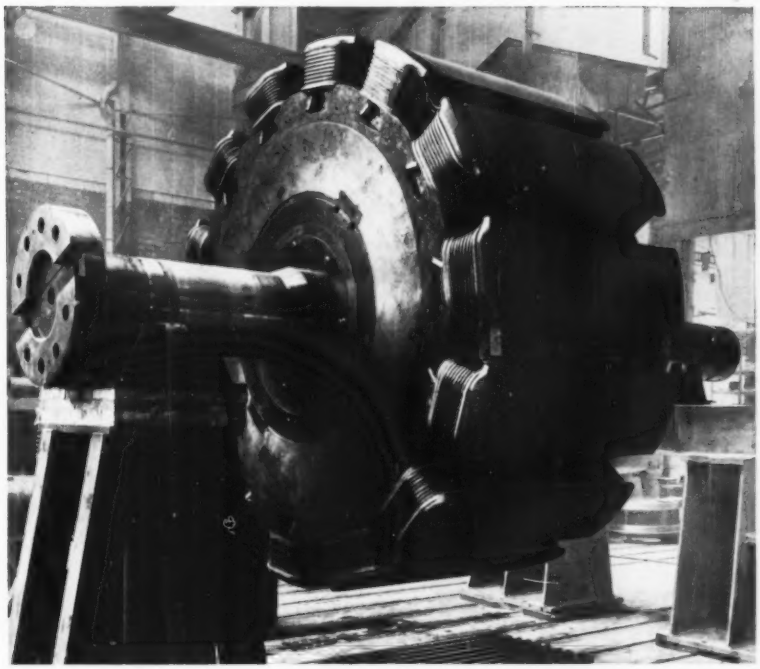


Fig. 7.
Rotor for 32,500 kW 428 r.p.m. vertical shaft alternator

each. The poles, which are built up from laminations with thick cast steel end plates, are fixed to the rotor in dovetail slots and held by taper side keys. The complete rotor weighs 107 tons.

The alternator is of the two-bracket type in which the thrust bearing for carrying the rotor is located above the stator, and there is a guide bearing on each side of the rotor. The upper guide is combined with the thrust bearing in a common chamber and both are of the pivoted pad type. The thrust bearing supports the weight of the rotor and also the hydraulic thrust from the turbine runner, amounting to a total of 235 tons. This load is transferred to the foundations through the stator frame and generator support. The oil supply to the bearings is obtained from electrically driven "Imo" pumps, and the thrust bearing is so arranged that if the oil supply fails, sufficient oil is retained in the bearing by means of an outlet weir to enable the set to be brought to rest without damage to the bearing.

The normal oil supply is from an A.C. motor-driven pump, with a D.C. motor-driven pump as an automatic standby controlled by a flow relay in the delivery branch from the main pump. The oil is cooled by water circulation in a single vertical cooler. This lubrication system is completely separate from the one already described for the turbine bearing.

The lower guide bearing is of the sleeve type, split into halves for dismantling, and its oil supply is from the same system as for the upper bearing. The lower guide bearing is carried in the lower bracket below the stator, and this bracket also carries the brakes which are Ferodo lined and bear on the under surface of the rotor when shutting down. The use of these brakes avoids prolonged running at slow speeds which is detrimental to the thrust pads. Compressed air for the brakes at a pressure of 55 lb/sq. in. is obtained through a solenoid operated valve and reducing valve from a standard 'English Electric' type AC2 compressor which is common to all four sets. The compressor equipment also delivers air at 300 lb/sq. in. for occasional charging of the governor receivers. The brakes can also be supplied with

oil at 2,000 lb/sq. in. from a hand-operated pump to lift the rotor when inspection or replacement of the thrust pads is required.

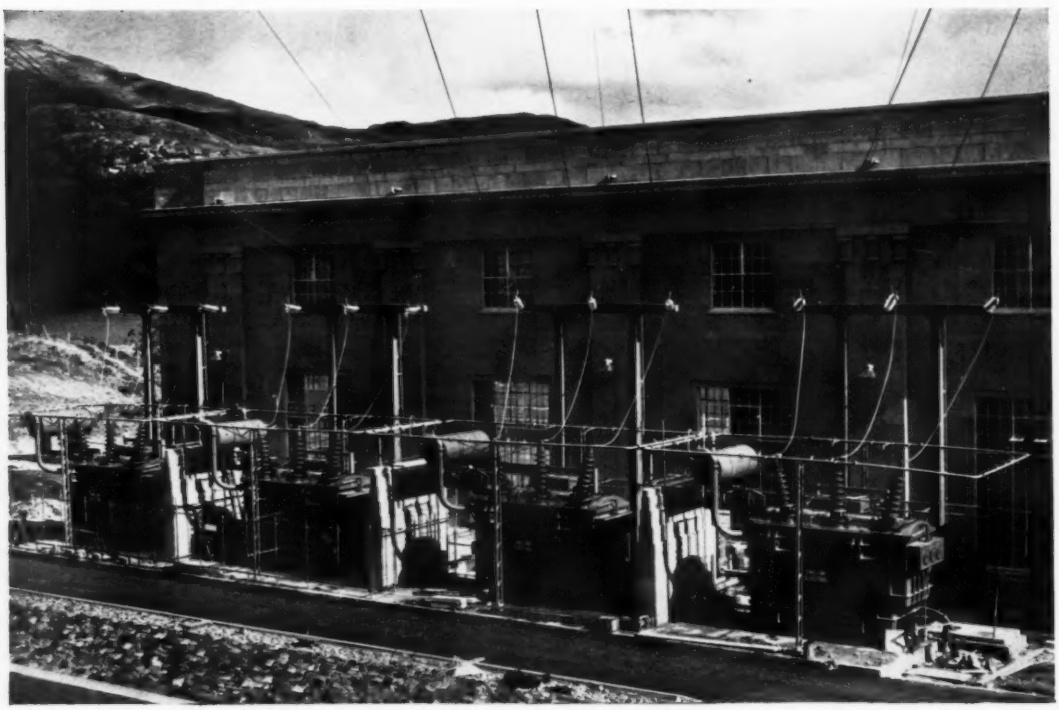
The main and pilot exciters are directly coupled to the upper end of the alternator shaft. The pilot exciter is self-excited and supplies the field of the main exciter at a constant voltage, the current to the field being controlled by an automatic voltage regulator. The output of the main exciter is connected through a main field circuit-breaker to the alternator rotor. The sliprings are located above the main exciter and the connections to the rotor are taken down the centre of the shaft.

The alternator and exciters are totally enclosed, air being circulated by fans fitted to each side of the rotor. Six vertical coolers are located round the stator. Part of the air is diverted to the exciters and this air returns through a filter to ensure that no carbon dust is carried from the brushes to the alternator.

In addition, some air can be diverted into the turbine room through louvres in the top of the stator air ducting. Make-up air enters the alternator through further louvres in the plinth and passes through filters.

A CO_2 fire extinguishing equipment is common to all four sets and is operated by electrical push buttons which release two sets of cylinders to the appropriate alternator through two sets of nozzles placed near the top and bottom fans. The first set of nozzles is arranged to give a quick discharge so that a heavy concentration may be built up rapidly, and the second set admits gas gradually to ensure that the concentration is maintained for a sufficient time to allow the machine to shut down and the fire to be extinguished. The cylinders are located in a pit below floor level in the turbine room. When CO_2 is released to any machine, pressure-operated devices automatically close the louvre doors to prevent escape of the gas.

Fig. 8. *The four* 35,000 *kVA* 11/132 *kV generator transformers*



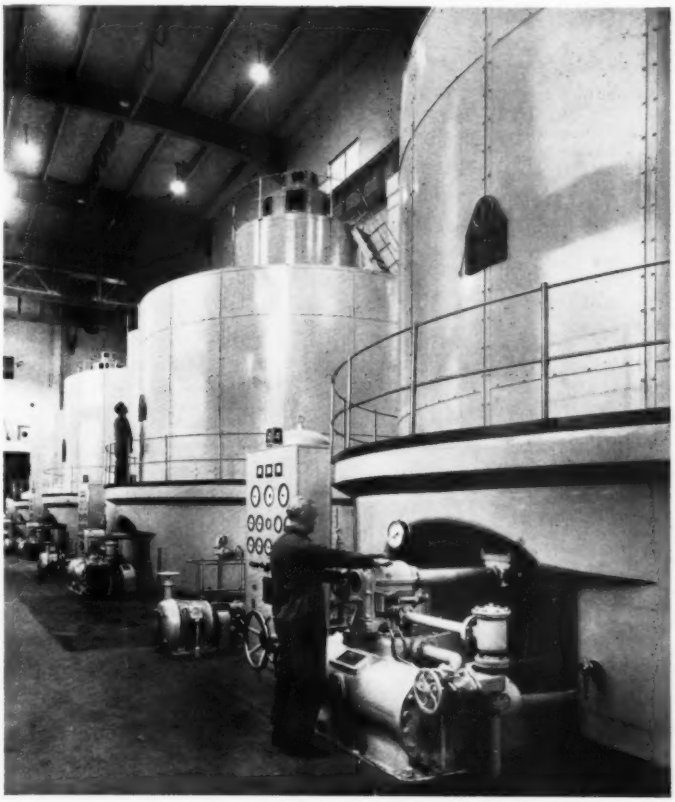


Fig. 9. Downstream side of generating sets, showing turbine governor and instrument panel

The water supply for the air and oil coolers is obtained from motor driven pumps. The pumps for the four sets, with an additional standby pump of double the size, are grouped together in a pit below normal tail water level in an annex to the power station.

Transformers

Each alternator is connected solidly to a step-up transformer through two 1 sq. in. single core cables in parallel per phase, and the power from each transformer is transmitted by a 132 kV overhead line to the switching station at Inveruglas, about one mile from the power station. The transformers, shown in Fig. 8, are 3-phase units each rated at 35,000 kVA, and step-up from 11 to 132 kV. Cooling is by forced oil circulation with duplicate water coolers and oil pumps which are located in two chambers between the transformers, each chamber containing the cooling equipment for two transformers. The cooling water supply is taken from the system supplying the alternators and turbines.

The high voltage winding is provided with tappings to give from 0 to +15 per cent. in 10 steps for the addition, at a future date, of on-load tap changing gear.

Mulsifyre fire protection is provided for the transformers, and this also covers the cable galleries in the power station.

Control

The turbines and alternators are manually controlled, starting and stopping of a turbine being effected by the levers situated on the top of the actuator.

Most of the gauges and indications for a turbine and alternator are grouped on the instrument panel at the left-hand side of the governor, as seen in Fig. 9. The equipment on each panel includes a flashing alarm beacon with three 6-way alarm facias giving indication of the following conditions :—

Condition	Initiating device
Governor oil pump failure	Flow relay.
Governor oil pressure low	Pressure relay.
Alternator lubricating oil flow failure	Flow relay, time delayed.
Thrust bearing low oil level	Level switch.
Low air pressure (on one set only)	Pressure relay.
Thrust bearing temperature high	Thermometer.
Upper guide bearing temperature high	Thermometer.
Lower guide bearing temperature high	Thermometer.
Turbine guide bearing temperature high	Thermometer.
Thrust bearing oil outlet temperature high	Thermometer.
CO_2 released	Auxiliary contact on release solenoid.
Faulty air brakes valve	Pressure relay.
Main valve trip on fault	Tripping relay.
Air inlet temperature high	Thermometer.
Air outlet temperature high	Thermometer.

Fig. 10. *The control room*

The equipment of each panel also includes :—

Pipeline water pressure gauge.
Spiral casing water pressure gauge.
Alternator indicating wattmeter.
Thermometers corresponding to the alarm indications listed above.
Running-hours recording meter.
Draught tube vacuum gauge.

Indicating lamps for :—

Alternator standby lubricating oil pump running.
Turbine standby lubricating oil pump running.
Air brakes on.
Turbine inlet valve open or closed.
Governor oil flowing.

Control switches or push buttons for :—

Alternator brakes.
Emergency trip.
CO_2 release.
Alarm acceptance.
Alarm lamp test.

Protection is provided to ensure the automatic shut-down of a set under any of the following conditions :—

Thrust bearing oil flow failure.
Governor drive failure.
Governor oil pressure low.
Overspeed.
Over-voltage.
Bus-zone fault.
Electrical fault on alternator, transformer or transmission line (by Translay protection).
Main transformer fault (by Buchholz relay).
Main transformer winding temperature high.
Unit transformer fault (by Buchholz relay).

Control of the auxiliary motors is not carried out from the instrument panel but by push buttons located on the starters which are grouped in a unit board on the upstream side of the set.

When a generating set is running, synchronising and load control is carried out from the control room, shown in Fig. 10. This contains a control desk for the generating sets, a control board with mimic diagram and synchronising instruments, the automatic voltage regulators (left) and the relays and temperature indicating instruments (right).

The main control of the switchgear and the sets is effected by telephone-type equipment, operating on 50 volts with light currents, and therefore telephone-type cables (20 lb per mile, 1/.036 in) are used. The load, speed, voltage and power factor of each machine are controlled from the desk, where indications are given of the load, power factor, rotor current and rotor voltage. The control and position indication for the generator circuit-breakers are also located on the desk together with alarm facias, of the same type as those used on the turbine instrument panels, to give indication of the following fault conditions.

Each generating set :—

Governor oil pressure failure.
Governor drive failure.

Generator bearing lubricating oil flow failure.
Mechanical failure.
Overspeed.
External fault.
Over-voltage.
Winding temperature high.
Generator earth fault.
Breaker tripped.
Automatic voltage regulator cut out.
Internal fault.
Cooler water failure.
Transformer oil pump failure.
Main transformer Buchholz gas.
Unit transformer Buchholz gas.
Low air pressure.

Each feeder circuit :—

Primary protection operated.
Back-up protection operated.
Breaker tripped.
Low air pressure in circuit-breaker local receiver.
Protection out (except Shira feeder).
Valve failure in carrier current equipment (except Shira feeder).

Bus-section and bus-zone circuits :—

Breaker tripped.
Primary protection operated.
Low air pressure in circuit-breaker local receiver.
Tripping relay operated.
Protection unstable, zone 1.
Protection unstable, zone 2.
Protection out, zone 1.
Protection out, zone 2.
Bus-zone tripped, zone 1.
Bus-zone tripped, zone 2.

Miscellaneous circuits :—

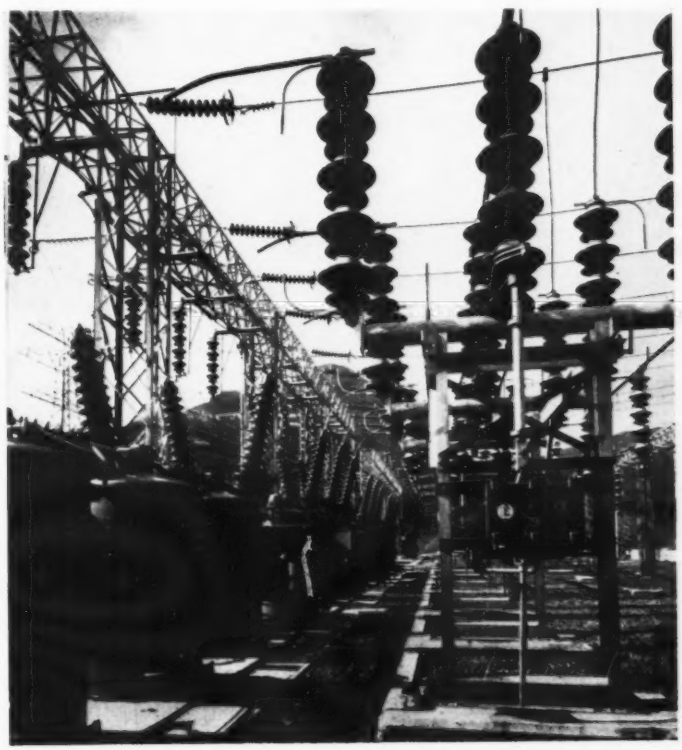
Fuse alarms.
Pilot alarm.
Battery charger failure.
Telemetering fuse alarm.
Trip supply failure.
Fire protection operated.
Carrier current equipment power unit fault.
Carrier current equipment power unit failure.
Main receiver low air pressure.

Control of the feeder and bus-section circuit-breakers is carried out from the control board, the mimic diagram on which shows the main electrical circuits and also the turbines and alternators.

The method of circuit-breaker control is novel. If it is desired to close a breaker, the appropriate control selector switch is rotated which automatically connects the synchronising instruments to the circuit concerned. Synchronising is then carried out manually, and when synchronism is reached the breaker is closed by pressing a small push button in the centre of the control switch. To trip the breaker the same push button that is used for closing is pressed without first operating the selector switch.

The automatic voltage regulators for the alternators are behind glass doors on the left-hand side of the control room, and the relays, with the alternator and transformer temperature indicating instruments, are on the right-hand side. The

Fig. 11. *Part of the* 132 *kV switching station at Inveruglas, during construction*



purpose of the glass doors was to give a flush appearance to the control room although using projecting-type instruments and relays.

A local telephone exchange is included in the control desk which is also served by a G.P.O. line. There is also direct telephone connection with Tummel control centre, and Windy Hill switching station of the British Electricity Authority about 25 miles distant, over the 132 kV transmission lines by carrier current equipment.

Auxiliary Switchgear

In a hydro-electric station the auxiliary switchgear is very simple, particularly when a unit system is adopted, as can be seen from the key diagram. The motor-starter boards are normally supplied from a unit transformer but an alternative supply is available from the common services board. This board is supplied by an auxiliary impulse-type water turbine driving a 450 kW 415 volts alternator, and also at present from the temporary diesel engine station built for the construction work of the scheme. The common services board is composed of 'OB3' air-break draw-out type circuit-breaker units and 'Combination' fuse-switches. The lighting and heating boards are also of the 'Combination' fuse-switch type.

D.C. supplies for the control of the generating sets and emergency services are obtained from a 50 volt 100 ampere-hour battery and a 110 volt 300 ampere-hour battery, and are distributed through a live-front D.C. board in which the constant-voltage battery chargers are also included.

Transmission Lines and Switching Station

As previously mentioned, the high-voltage terminals of the step-up transformers are solidly connected to two double-circuit 132 kV transmission lines, each approximately one mile long, to the switching station at Inveruglas.

The switching station, of which a section during construction is shown in Fig. 11, is of the single busbar type. There are four generator circuits, initially six feeders, and one bus-section. Three of the feeders are to Glasgow, one to a neighbouring hydro-electric scheme at Shira, for which The English Electric Company is also supplying most of the plant, and two connect with the 132 kV system of the North of Scotland Hydro-Electric Board in north-east Scotland. Space is included for a total of 16 circuits and the bus-section.

The structures for supporting the busbars and isolating switches are of steelwork. The circuit-breakers are of the bulk-oil dead-tank type and have arc control devices of the latest design which enabled the internal diameter of the tanks to be reduced from 62 in. to 54 in. with a corresponding reduction in the oil content from 1,000 to 600 gallons per phase. The breakers are rated at 1,500 MVA and are provided with high-speed pneumatic closing mechanisms. They are, as already stated, normally controlled from the power station by means of direct pilot wires, but provision is made for local electrical control at the circuit-breaker.

The isolators are of the usual rotating centre pillar type, hand operated but with remote indication of position.

The compressors, which provide air at 150 lb per square inch for operating the breakers, are housed in a plant house which also contains the local relay board, a 110 volt 150 ampere-hour battery and a battery board.

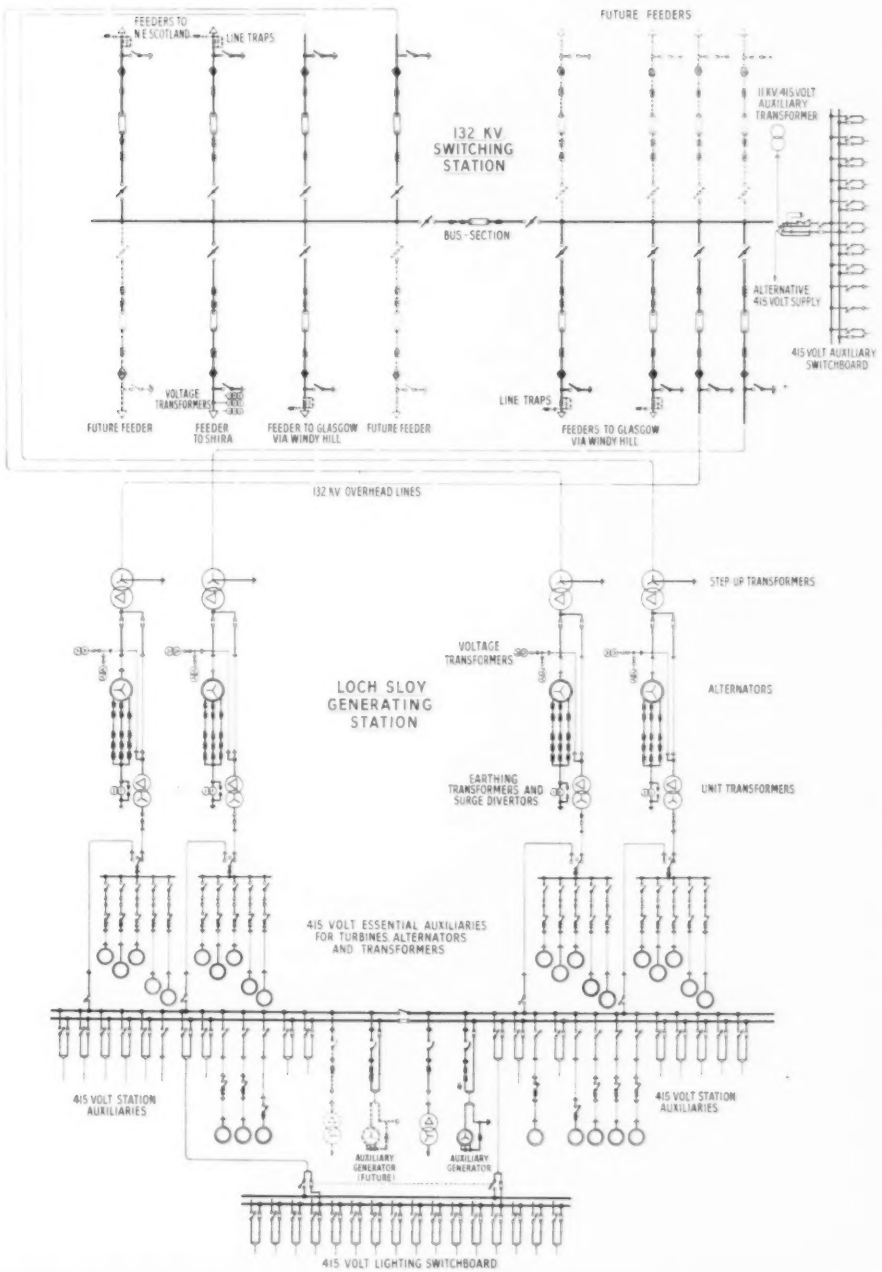
Protection

Protection of the feeders, except the Shira feeder, is by telephone equipment using carrier currents, with back-up overload protection. Line traps are provided which block the high frequency carrier signals so that they are not fed into the busbars, and the signals are led to the carrier current equipment by means of co-axial cables. The Shira feeder, which is a two-way feed, is protected by ratio balanced protection energised from a 132 kV wound voltage-transformer.

Protection of the interconnectors to the power station is by overall Translay which covers the zone from the generator neutrals to the busbar side of the generator breakers including the generator windings, cable, transformer, transmission line and breaker. Negative phase sequence protection is also included for the generator.

The busbars are protected by bus-zone protection divided into two sections which correspond with the sectioning of the busbars by the bus-section switch which is included in both sections to give overlapping.

PLATE IV **Key diagram of main and auxiliary electrical system**



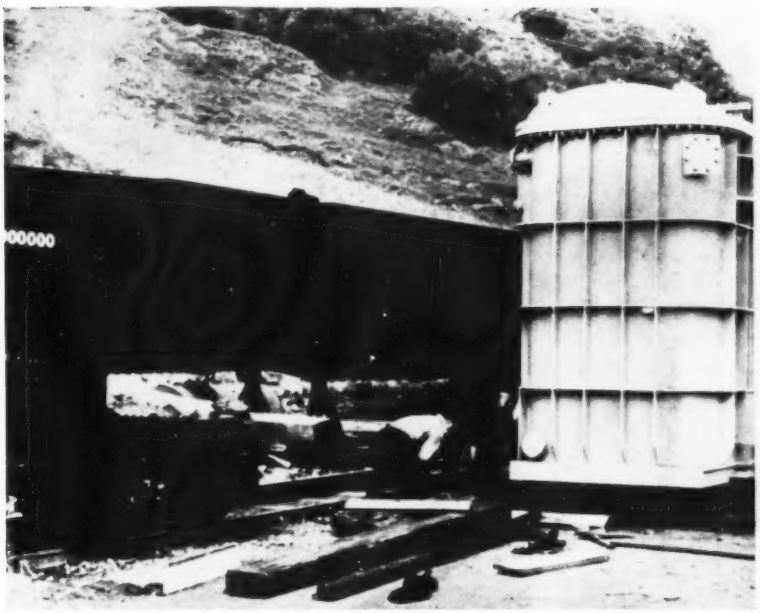


Fig. 12.

A generator transformer weighing 71 *tons being off-loaded at Inveruglas*

Transport

A project the size of Loch Sloy involves not only the design, drawing and manufacture of the mechanical and electrical equipment but also the problem of delivery to site and erection.

The first parts to be delivered were the draught tubes which although not heavy were rather bulky, as they were delivered in one piece to avoid site welding. Each spiral casing with its foundation ring weighed 42 tons and although its weight was not excessive, it was the heaviest part to be transported by road all the way, and the width was considerably beyond the normal transport limits.

The alternator rotors with poles removed weighed $84\frac{1}{2}$ tons each and were transported by rail to a special siding built for constructional purposes at Inveruglas. There was no crane of sufficient capacity at the siding for off-loading, and the transfer to the road vehicle for transport to the power station was carried out by jacking.

The transformers each weighing 71 tons were transported in a similar way, but a special transformer rail-waggon was used. Fig. 12 shows a transformer being off-loaded at the siding.

The alternator stators were despatched in halves, each weighing $33\frac{1}{2}$ tons, and like the spiral casings they were transported by road throughout.

Erection

The first parts to be erected were the draught tubes which had to be positioned before any of the power station steelwork was built, and a temporary crane was used. The photograph reproduced in Fig. 13 was taken late in 1947 when the third draught tube was being placed in position. This illustration shows part of the concrete portion of the draught tube and the concrete foundations for the power station steelwork ; the ground is being cleared for the pipelines, and the railway bridge for passing over them is already finished.

Generally, after placing the draught tubes in position very little erection work can be done on the plant until the power station crane is operating and protection from the weather is built. At Loch Sloy, however, the civil progress was such that erection of the turbines had to proceed before the walls were completed, and with the prevailing weather the working conditions were at times not good. Fig. 14 shows the state of erection in the

Fig. 13. *Placing the third draught tube in position*

spring of 1949 when three of the turbine spiral casings were in position. The inlet pipe and relief valve branch are also erected on the set at the far end of the station. The concrete walls are being built from scaffolding on the inside and the outside of the station.

It is worth recalling that when the first generating set was completed, Sir Edward MacColl of the North of Scotland Hydro-Electric Board set it in motion for the first time, without any previous trial run, at 3.15 p.m. on the 18th February 1950. The set was then taken up to full speed and ran entirely satisfactorily. This was a great tribute to all who had worked on the design, manufacture, and particularly erection, overcoming many difficulties. The first set was put into commercial service on 6th March 1950, and the remaining three sets on the following dates :—

2nd set .. .. 20th July 1950.
3rd set .. .. 30th November 1950.
4th set .. .. 1st February 1951.

Acknowledgments

The author thanks the North of Scotland Hydro-Electric Board for their kind assistance in providing data for this article.

The consulting engineers were :—Messrs. James Williamson and Partners, for the civil engineering. Messrs. Kennedy and Donkin, for the mechanical and electrical power station plant. Messrs. Merz and McLellan, for the switching station.

Fig. 14.
Three spiral casings in position during erection

Emergency Stopping of Slipring Induction Motors

By A. J. RICHES, B.Sc. (Eng.), M.I.E.E., Machine Design Department.

TWO ALTERNATIVE FORMS of electrical braking can be employed for the normal or emergency stopping of drives powered by slipring induction motors. Common instances are flywheel motor-generator sets for Ward Leonard winding and rolling mill equipments, A.C. winding equipments, and rubber processing machinery. The electrical power demand for braking can be either A.C. or D.C. When A.C. power is used, the style of braking is known as plugging, or counter-current or reverse power, and when D.C. power is employed the form of braking is referred to as dynamic braking.

The purpose of this article is to describe the salient features of the two systems and to indicate their relative differences.

A.C. Braking

With this system, the main connections of which are shown in Fig. 1, braking is effected by reversing the direction of rotation of the stator field relative to the rotor and loading the rotor circuit on to a resistance which may be of either the liquid or metallic type. The resistance is usually the normal starting and accelerating resistance. Reversal of the stator field is accomplished by interchanging any two of the three supply lines connected to the stator and for this purpose a double pole or triple pole switch R is provided in addition to the normal switch F, the two switches R and F being suitably interlocked to prevent simultaneous closing. As will be explained later this form of braking results in :—

(*a*) an appreciable energy demand from the supply system,

(*b*) high dissipation of energy in the rotor resistance, equal to (*a*) plus the net braking work performed,

(*c*) possible increased ohmic value of the rotor resistance,

(*d*) a slipring voltage of at least twice the normal open circuit standstill value.

In cases where under normal running conditions the motor operates with the external resistance short-circuited, means must be adopted to reintroduce the resistance before braking is initiated.

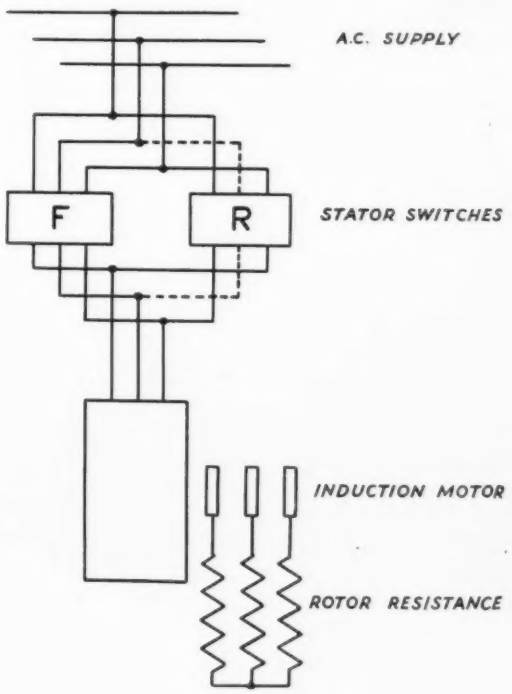


Fig. 1. Main connections for counter-current braking of induction motor

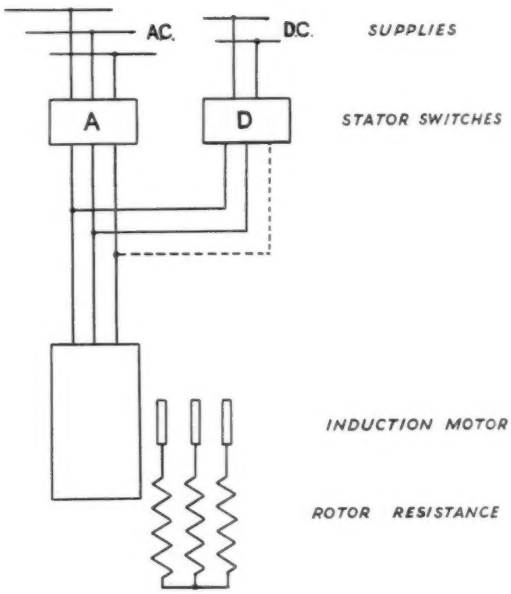


Fig. 2. Main connections for dynamic braking of induction motor

Upon the motor being brought to rest, the stator must be disconnected from the supply system to prevent the motor from running up in the opposite direction of rotation.

D.C. Braking

The main connections for this system are shown in Fig. 2, when braking is effected by disconnecting the motor from the A.C. supply system by opening the normal switch A and then connecting a source of D.C. to two (or three) phases of the stator through a double pole switch D. Switches A and D are interlocked to prevent simultaneous closing, and the poles of switch D must be insulated for the A.C. supply voltage. The D.C. excitation on the stator produces a stationary field system and the motor becomes an alternator being driven by the stored energy of the coupled load, with the generated A.C. power in the rotor dissipated in the rotor resistance which, as with A.C. braking, may be of the liquid or metallic type and is usually the normal starting and accelerating resistance.

It is interesting to note that it is not possible to choose the D.C. excitation voltage as this pressure is the IR drop of the stator windings, i.e., the product of the excitation current required to produce a given braking torque and the resistance of the stator windings as connected for excitation. Excitation power requirements for low voltage motors (400 volts) result in low values of voltage with relatively high values of current. D.C. for excitation of the stator may be obtained from (1) an auxiliary supply (if available and suitable), or (2) a motor-driven exciter, or (3) a metal rectifier. When an auxiliary D.C. supply is available it is usually at 110 or 220 volts and a series resistance is required to absorb the unwanted part of the auxiliary voltage. The loss in the series resistance (especially with low voltage motors) is usually prohibitive in relation to the excitation loss in the stator winding itself and for this reason auxiliary D.C. supplies are seldom used.

When D.C. exciters are used design difficulties are encountered with the low voltages and heavy currents required by low voltage motors, but regardless of excitation voltage the exciter set must be running continuously in order to provide immediate availability of braking power. When braking equipment is installed for emergency stopping as distinct from normal continuous routine stopping, the D.C. exciter introduces standby losses and additional maintenance. A metal rectifier is a preferred source of D.C. as standby losses and maintenance are both negligible and rectifiers can be arranged for any desired values of excitation voltage and current without difficulty.

Star connected stators are to be preferred to delta connected stators for excitation purposes, as the latter connection results in the excitation of all three stator phases and for a given motor requires a higher excitation current at a proportionally lower voltage than a star connected stator. With star connected stators the excitation of two phases in series with the third phase open-circuited usually results, for a given braking torque, in lower excitation power compared with the excitation of all three phases resulting from the excitation of two phases in parallel and connected in series with the remaining phase.

As with A.C. braking, motors normally operating with short-circuited external resistance must have the resistance reinserted before initiation of braking. Upon the motor being brought to rest, means must

be introduced to remove the D.C. excitation to prevent unnecessary heating of the stator. As braking effort is obtained by the generation of a rotor voltage resulting from the rotation of a polyphase winding (rotor) in a stationary D.C. field (stator), it is clear that at low speeds the rotor voltage will be very low, and zero at standstill, and thus the braking effort will be slight. This feature is of no real practical importance since at low speeds the frictional torque of the driven machinery acts as a retarding torque to bring the drive to a final stop. Features of D.C. braking are :—

(*a*) No power demand from normal A.C. supply.
(*b*) Provision of suitable D.C. supply.
(*c*) Economic D.C. excitation power demand.
(*d*) Rotor resistance dissipation equal only to net braking effort performed.
(*e*) Maximum generated rotor voltage of the same order as the normal open circuit standstill voltage.
(*f*) Ohmic value of braking resistance usually within the range of the normal starting resistance.

The Ideal Case

The relative features of the two systems of braking may be seen from Fig. 3, illustrating the ideal case of uniform braking torque and the energy in the drive being all kinetic. With constant braking torque (BD) from full speed to standstill, deceleration will be uniform in a time of say, T seconds, and the shaft h.p. (BE) will fall linearly to zero. Area ABE x T will be equal to the h.p. seconds stored energy in the drive at full speed and equal to the net braking effort performed, and also equal to the rotor resistance dissipation with D.C. braking. With A.C. braking when the stator field is reversed with the rotor running at full synchronous speed, the motor slip is practically 200 per cent. which falls to 100 per cent. with the rotor at rest. As slip is defined as the ratio of rotor copper loss to power across the air gap, i.e., synchronous h.p. (torque), the rotor copper loss is equal to synchronous h.p. multiplied by slip. At full speed the slip is 200 per cent. and rotor loss (AC) is equal to twice the braking torque, and at standstill the slip is 100 per cent and the rotor loss (ED) is equal to the braking torque. In Fig. 3 the

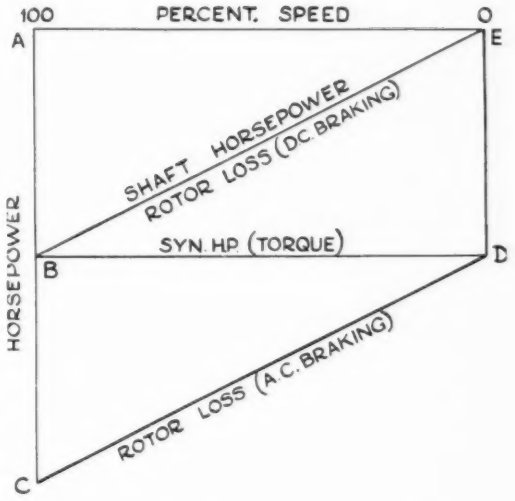


Fig. 3. Comparative A.C. and D.C. braking efforts

value of the rotor loss between full speed and standstill is shown by the line CD. The energy demand (less stator losses) on the supply is area BCDE, equal to the difference between the rotor loss and the net braking effort. Denoting the stored energy in the drive at full speed by E, Table A follows from the foregoing :—

	D.C. Braking.	A.C. Braking.
Net braking effort ..	E	E
Braking power (torque)	2E	2E
Loss in rotor resistance	E	3E
A.C. power from supply	—	2E

The Practical Case

Practical illustration of the foregoing is afforded by reference to an actual case submitted by a well-known rubber company to whom a 500 h.p. slipring induction motor had been supplied many years ago for driving a group of rolls through a gear train. Emergency stopping of the rolls for the safety of operating personnel is an important feature in the processing of rubber. The existing method of emergency stopping was not thought to be entirely satisfactory and a request for a recommended method of electrical braking was received. This raised the question whether or not to ' plug.'?

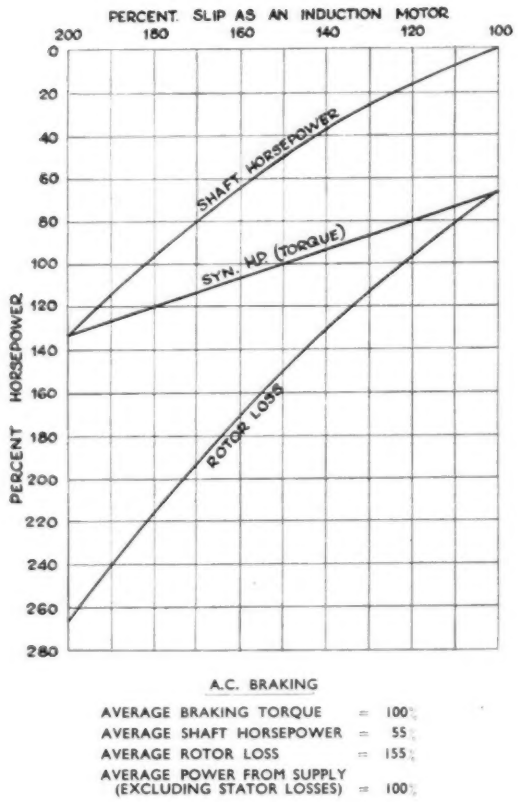

PERCENT SLIP AS AN INDUCTION MOTOR
200 180 160 140 120 100
0 20 40 60 80 100 120 140 160 180 200 220 240 260 280
PERCENT HORSEPOWER
SHAFT HORSEPOWER
SYN. HP. (TORQUE)
ROTOR LOSS
A.C. BRAKING
AVERAGE BRAKING TORQUE = 100%
AVERAGE SHAFT HORSEPOWER = 55%
AVERAGE ROTOR LOSS = 155%
AVERAGE POWER FROM SUPPLY (EXCLUDING STATOR LOSSES) = 100%

Fig. 4. Characteristics of A.C. braking on induction motor driving group of rolls through gear train

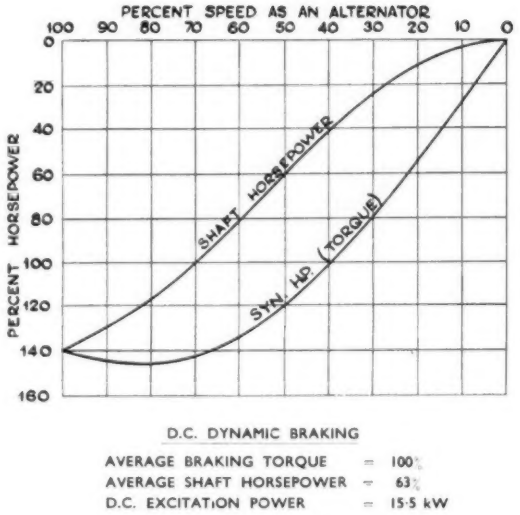

PERCENT SPEED AS AN ALTERNATOR
100 90 80 70 60 50 40 30 20 10 0
0 20 40 60 80 100 120 140 160
PERCENT HORSEPOWER
SHAFT HORSEPOWER
SYN. HP. (TORQUE)
D.C. DYNAMIC BRAKING
AVERAGE BRAKING TORQUE = 100%
AVERAGE SHAFT HORSEPOWER = 63%
D.C. EXCITATION POWER = 15·5 kW

Fig. 5. Characteristics of D.C. braking on same induction motor as Fig. 4

Both A.C. and D.C. braking were investigated and the resulting comparative characteristics are shown in Figs. 4 and 5, where it will be noticed that each form of braking has been arranged to produce similar average braking torques. Although the two alternative braking torque curves are not of similar shape and neither is constant at full load torque (as in the ideal case), their average torques are nevertheless the same and for all practical purposes the stopping times may be regarded as comparable.

With D.C. braking the average h.p. dissipated in the rotor resistance is 63 per cent. with a D.C. excitation demand of only 15.5 kW. With alternative A.C. braking, for an average braking effort of 55 per cent., the demand on the supply (excluding stator losses) amounts to 100 per cent., resulting in a rotor resistance dissipation of 155 per cent. (over 750 h.p.). The ratios of supply demand to net effort, and dissipation to net effort, are approaching the values in Table A, which it will be remembered are based upon constant braking torque. The difference in the net braking efforts of 63 per cent. and 55 per cent. is again due to departure from uniform braking torques in the alternative systems. Both forms of braking use a fixed resistance, as the stopping time is too short (order of 1 to 2 seconds) to permit reduction in value to increase the average braking torques.

The rubber company's engineers chose the D.C. system despite the additional cost of providing a metal rectifier for excitation purposes. The main reasons for the decision were (1) lowered demand for braking power, (2) existing liquid resistance of insufficient capacity to handle the dissipation required by the A.C. system, and (3) avoidance of the imposition of at least twice normal slipring voltage on an old motor.

Improvements and Modifications to the Farnboro Engine Indicator

By R. W. STUART MITCHELL, M.Sc., A.R.T.C., A.M.I.Mech.E., A.M.I.C.E.,
Chief Development Engineer, Diesel Engine Division.

EVERY ENGINEER who has taken a course in heat engines in a technical college or university is familiar with the slow-speed spring and pencil indicator giving a P.V. diagram, the area of which represents the " indicated work " of the cylinder. This type was evolved and was highly satisfactory for the slow-speed steam engines of the period around the commencement of the present century. However, as the internal combustion engine developed and rotational speeds increased, the " steam engine indicator " became totally inadequate because of two major defects, namely, the elasticity of the normal cord drive and the inertia of the piston and pencil mechanism.

Neglecting the intermediate period of the " optical " indicators such as the Watson-Dalby which were really only modifications of the original in an attempt to reduce the inertia, the first successful high-speed indicator designed primarily for internal combustion engines and utilising an entirely novel principle, was the " Farnboro." This was developed at the Royal Aircraft Establishment and was first described in a paper to the Institution of Mechanical Engineers in 1923. Although it has a number of defects and many attempts have been made to improve it, it is still in widespread use, notwithstanding the ever increasing popularity and diversity of modern electronic instruments. Its chief virtues when compared with its electronic competitors undoubtedly lie in its robust construction, which makes it an everyday workshop instrument rather than a laboratory one, its lack of " temperament," and the fact that it can be understood and operated successfully by the average mechanical engineer after ten or fifteen minutes explanation and instruction. There is virtually no limit of speed at which the Farnboro can be operated although there is a very small inertia effect. It is not, in the author's opinion, any exaggeration to say that the development of the Farnboro indicator has been one of the landmarks in the history of the development of the modern internal combustion engine.

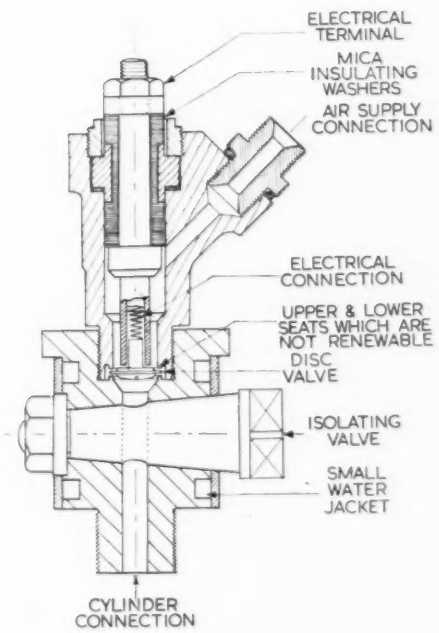


Fig. 1. Sectional arrangement of standard Farnboro disc valve unit

The principle of operation of the indicating unit is that of the " balanced " disc valve, a typical example of which is shown in Fig. 1. There is a very light disc valve which is free to move between two seats, one above the disc and one below. The movement of the disc is usually restricted to .007 in.—.010 in. and the seats are earthed electrically. One side of the disc is in communication with the engine cylinder and is thus subject to the cylinder pressure. The other side is connected to a source of high-pressure air which is fed to the unit through a hand operated valve. When the air pressure is the same as the engine cylinder pressure the disc floats between the two seats. The disc is made to form part of the primary circuit of a high-tension induction coil, and any movement of the disc from one seat to the other breaks the primary circuit, thus inducing a high-tension voltage in the secondary. This voltage is made to cross an air gap, where it appears as an intense spark and is used in the recording part of the apparatus.

In any given engine cycle there are two points when the pressure balance is obtained ; one when the cylinder pressure is increasing and one when it is decreasing. By varying the air pressure a series of points can be obtained on the recording card which cover the whole range of the cylinder pressure, although each pair of points will have been made for a different engine cycle. This latter feature is one of the weaknesses of the instrument as a research tool, since the record is an average one taken over a large number of cycles.

In the recording mechanism the card, actually a sheet of specially prepared paper 14½ in. × 7½ in., is positively driven from the engine at either crankshaft speed or half crankshaft speed and forms the time base. The actual record of each pressure balance is obtained when the high-tension spark is made to pass through and puncture the paper on the drum. The pressure axis of the diagram is obtained by the fact that the spark point is connected through a linkage to a piston which is acted upon by the same air pressure that acts on the disc, the piston being counterbalanced by calibrated springs. The position of the spark point relative to some fixed datum line is thus proportional to the cylinder pressure to a scale determined by the rate of the springs. A typical Farnboro diagram for a modern compression ignition oil engine is shown in Fig. 2.

A number of Farnboro indicators are in continuous use in The English Electric Company's Diesel Engine Development Department at Rugby, and have given very satisfactory service over a long period of years. Based on this experience, modifications have been made in the Development Shop

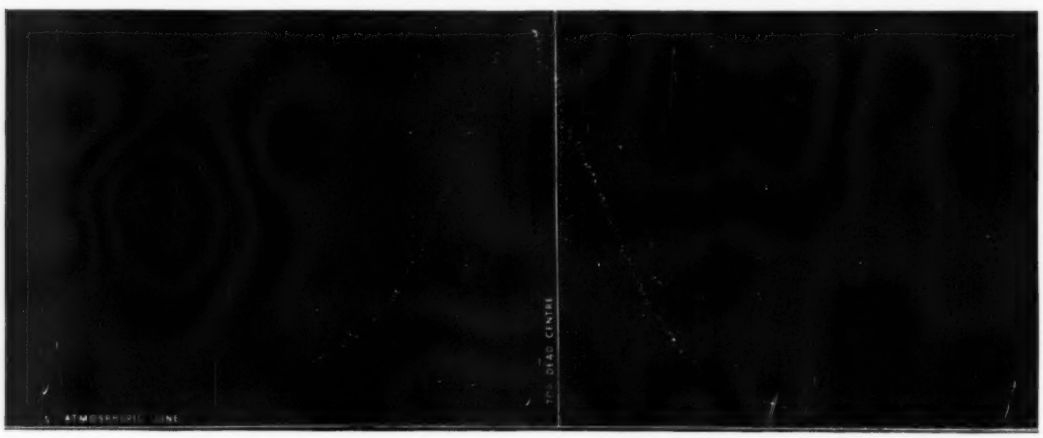


Fig. 2. Typical Farnboro diagram for a modern compression ignition oil engine

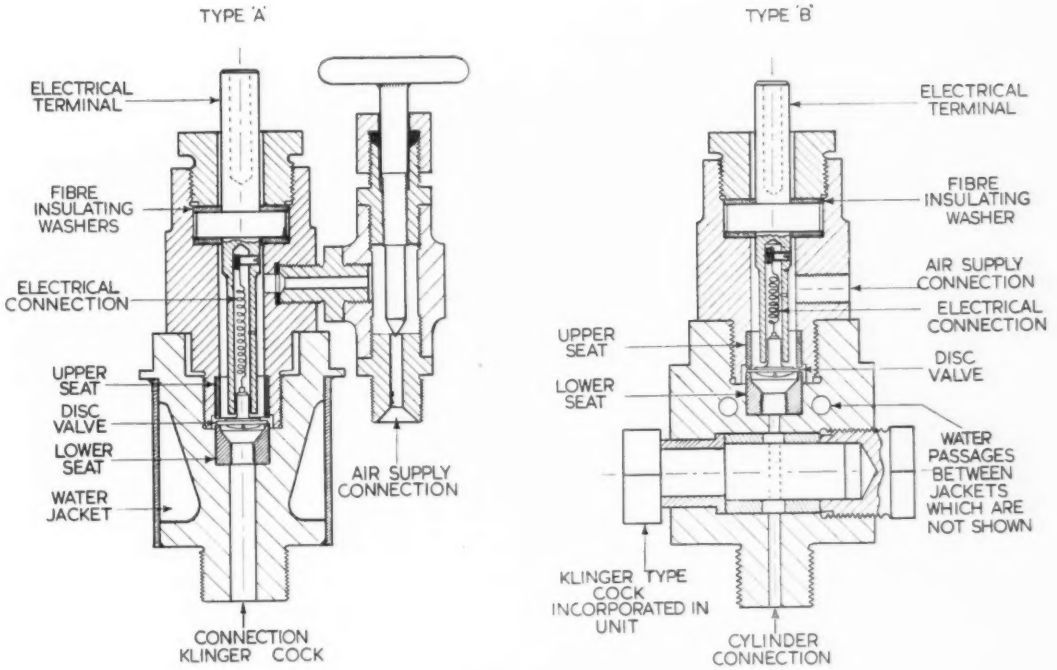


Fig. 3. Sectional arrangement of modified Farnboro disc valve unit

to the indicating unit which have improved its usefulness considerably. Seventy-six of these modified units are now in service, and Fig. 3 shows their sectional arrangement. This should be compared with the standard unit in Fig. 1. Both units operate in the same way and are dimensionally interchangeable. The main difference is in the method of ensuring electrical contact between the disc valve and its insulated centre piece. The standard units are fitted with a very light steel spring which screws into the threaded end of the disc valve and is designed to be a good fit in the insulated centre. It has been found in the Development Shop that this spring rusts very quickly and causes a high resistance in the 6 volt primary circuit of the induction coil. In the modified units this spring has been replaced by a light coiled stranded wire connection properly fixed at the ends to ensure the maintenance of a good electrical contact.

Other improvements are the use of stainless steel for the renewable disc valve seats and the insulated centre, and the provision of more adequate water space around the disc valve. The units can be cleaned without removing them from the engine ; a very important point in a busy development shop.

Tests have been carried out on the modified units against the standard units with satisfactory results, and the former have been used successfully to take light spring diagrams, and to indicate on a " K " size engine running on producer gas.

A new and successful indicator to read maximum cylinder pressures, utilising the modified Farnboro indicating units, has also recently been designed and developed at Rugby.

The normal Farnboro diagrams show two separate pressure points at the peak, which are very close together. These points represent the average peak or maximum cylinder pressure. This feature is made use of in the new indicator in the following manner.

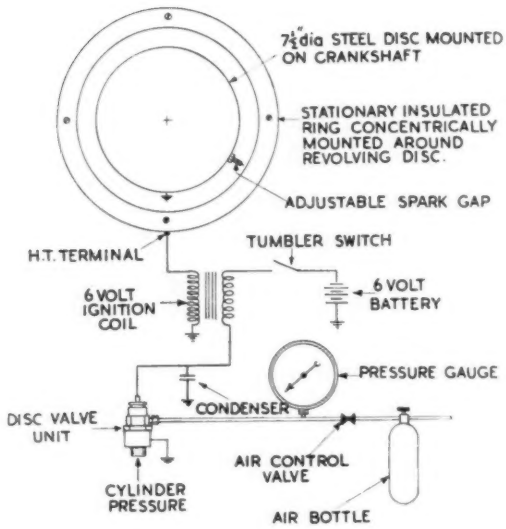


Fig. 4. Diagrammatic arrangement of sparking indicator

A $7\frac{1}{2}$ in. diameter steel disc rotates at crankshaft speed within a fixed and insulated steel ring, the whole being mounted on and driven from some convenient point on the engine under test. The electrical equipment is similar to that required for the normal Farnboro instrument and comprises a 6 volt 60 ampere-hour car battery, a 6 volt car ignition coil, a condenser and transfer switch. The compressed air to operate the modified disc valves is controlled by a needle valve, and the pressures are read on a 10 in. diameter dial gauge. The arrangement is shown diagrammatically in Fig. 4, and mounted on an engine in Fig. 5.

When the ignition coil is switched in, and air is applied to the disc valve through the control valve, two separate high-tension sparks can be seen across the adjustable gap between the rotating disc and the stationary insulated ring. As the air pressure is increased these two sparks come closer together, merge into one, and when the air pressure exceeds the maximum cylinder pressure, disappear completely. While the two sparks still exist separately, but just immediately before they merge into one, the air pressure is read on the dial gauge as the average maximum cylinder pressure.

The original instrument was developed on the "Vee" type research engine unit with 10 in. bore and 12 in. stroke. It has been applied to other engines with complete success. Check tests have been made against the complete Farnboro unit and the results have been entirely satisfactory.

The great advantage of the new instrument lies in the fact that it releases the Farnboro instruments for research and development work, and yet allows a constant check of peak cylinder pressures and compression pressures to be made during, for example, endurance runs of relatively long duration. It is remarkably inexpensive to make, as the cost need not be more than £10 complete.

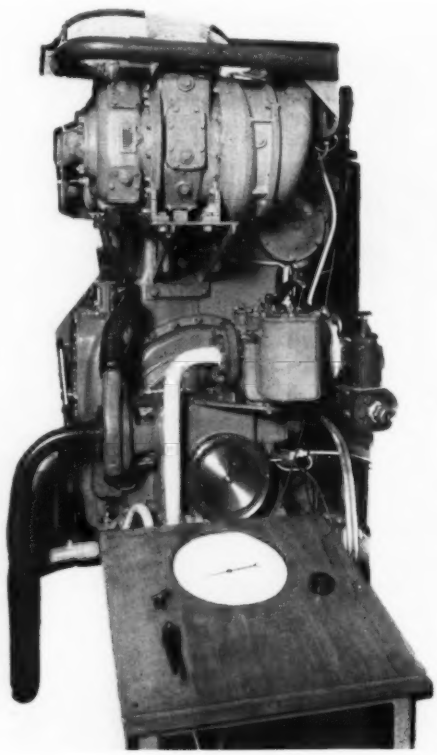


Fig. 5. The new indicator for maximum cylinder pressures, mounted on an engine

A Modern Merchant Mill at Jarrow

By H. S. BROWN, B.Eng., A.M.I.E.E., Metal Industries Division.

THE CONSETT IRON COMPANY LIMITED being financially interested in, and also managers of, the newly formed New Jarrow Steel Company Limited, decided in the late 1930's to build a new steel mill on the site of an abandoned shipyard in Jarrow, as this would provide alternative employment in a depressed area and at the same time a desirable increase in the output of merchant sections and narrow strip in the area. The new mill went into production in 1940 and the New Jarrow Company was absorbed into the Consett Iron Company in 1949.

The International Construction Company acted as the consultants for the whole project. The mill itself, excluding the re-heating furnace supplied by the International Construction Company, was manufactured by the Davy and United Engineering Company of Sheffield to the design details supplied by the Morgan Construction Company. The English Electric Company were the main contractors for almost the whole of the electrical equipment, including the main drives, auxiliary drives, distribution equipment, and also the cabling.

Although the mill has now been operating very successfully for 11 years, no description of the equipment has yet appeared in this journal. It remains, however, the most modern mill of its kind in Europe, in fact one of the best of its kind in the world, and it is thought that a description will still be appreciated.

The Mill

Before describing the electrical equipment, a brief description of the mill and its operation is desirable.

Rolled steel is received into the works in the form of billets and slabs 28 to 30 ft long. The billets range from 2 in sq. up to 4 in sq., and the slabs are in various sizes up to 9 in $\times$ $2\frac{1}{2}$ in.

The main products are :—

Angles ranging from 1 in $\times$ 1 in $\times$ $\frac{1}{8}$ in to 3 in $\times$ 3 in $\times$ $\frac{3}{8}$ in.

Strip, $1\frac{1}{4}$ in $\times$ .04 in to 9 in $\times$ .176 in.

Other products are :—

Flats, 1 in $\times$ $\frac{3}{16}$ in to 5 in $\times$ $\frac{3}{4}$ in.

Rounds, $\frac{7}{16}$ in to 2 in diameter.

Spring steel, $1\frac{1}{2}$ in $\times$ $\frac{7}{32}$ in to 5 in $\times$ $\frac{3}{4}$ in.

Crown tree sections, 5 in $\times$ $\frac{1}{4}$ in to 5 in $\times$ $\frac{1}{2}$ in.

Billets and slabs from the stockyard are loaded by crane on to a billet bank, whence they are fed down skids on to a live roller table feeding a re-heating furnace capable of heating up to 40 tons per hour. The billets and slabs are delivered from the furnace by a Hawthorn pusher and a pair of pull-out rolls which deliver the piece to the first stand of the mill.

The mill itself comprises a total of 13 stands. The first 7 of these stands are arranged in tandem to form the roughing train. This is followed by a single intermediate stand after which is the finishing train comprising 5 stands. All of the last four of these are required only when rolling certain strip gauges, and any of the stands can be removed when not needed for a particular rolling schedule. Edgers are provided in the roughing train after stands Nos. 2, 4 and 6.

Sections and bars when leaving the roughing train can pass through repeaters or be reversed on a skew-Y table into the intermediate stand and similarly repeated or handled by a second skew-Y table into the finishing train. Flats of all sizes and rounds below 1 in are repeated between the roughing train and intermediate stand, and also between the intermediate stand and the finishing train. The repeaters are removable.

Sections and bars are fed from the mill on to a double-sided cooling bed of the rack carry-over type. Shuffle bars transfer the pieces from the cooling bed to run-out tables feeding the cold shears and weighbridge.

Strip does not go on to the cooling bed, but is fed instead on to a vibrator table where the piece is looped on edge before being fed through vertical pinch rolls to a vertical coiler.

Main Drives—Machines

The electrical equipment is housed in two main rooms. One, the roughing mill motor room, houses the main drives for the roughing and intermediate stands, the main M.G. set, converting equipment, L.V. D.C. and A.C. switchgear and the control gear for both main drives and auxiliaries. The second, the finishing mill motor room, situated on the opposite side of the mill bay, houses the main drives for the finishing stands, the variable-frequency alternator set for the run-out tables, the M.G. set for the vibrator table and the control gear for these last two items.

These two motor rooms can be seen in Figs. 1 and 2.

The ratings of the motors driving the main and edger stands are given in Table I.

TABLE I

Stand No.	Motor Rating	
	h.p.	r.p.m.
Roughing—		
0 & 1	500	300/ 900
2	800	300/ 900
Edger No. 1	83.3/250	333/1,000
3 & 4	800	300/ 900
Edger No. 2	50/150	333/1,000
5	500	300/ 900
6	500	300/ 900
Edger No. 3	50/150	333/1,000
Intermediate—		
7	500	200/500
Finishing—		
8	500	200/500
9	500	200/500
10	500	240/600
11	500	300/800
12	500	300/800

It will be seen that, excepting stands 0 & 1 and 3 & 4 which are driven in pairs, each mill stand is individually driven.

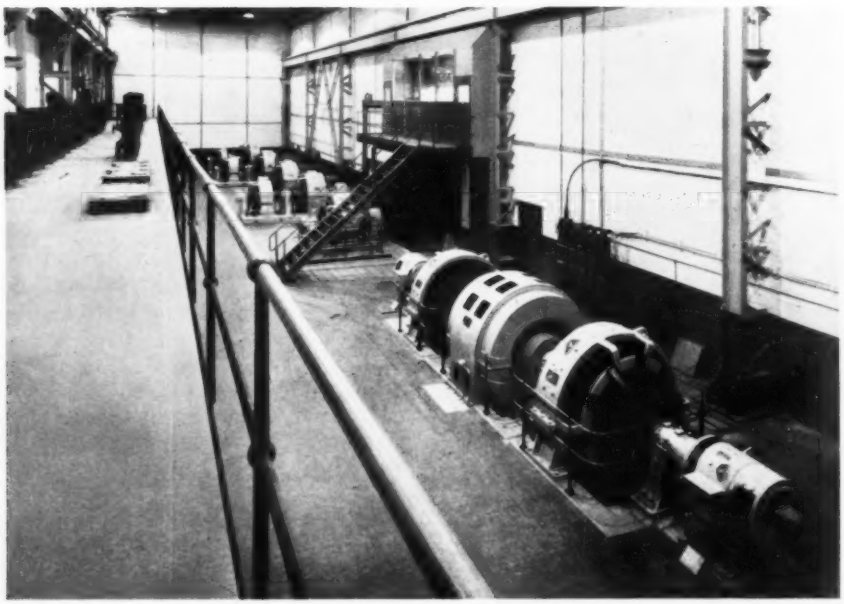


Fig. 1.

Roughing mill motor room, with main M.G.set in right foreground and roughing mill drives at far end. The main mill control pulpit is in the right-hand wall and the motorised rheostats for all drives are on the left

Fig. 2.

Finishing mill motor room, showing the five main driving motors with the pilot exciters for the vibrator coupled to the commutator end

The horizontal stand motors are fed from two variable voltage D.C. generators each rated at 1,750 kW 0/600 volts. One of these generators supplies the roughing and intermediate mill motors and the other the finishing train motors and the variable-frequency motor-alternator set. No provision is made for paralleling the two generators. The edger stand drives are supplied from generators coupled to the motor driving the preceding horizontal stand. The purpose of this arrangement is referred to later.

The two main generators are driven by a salient pole synchronous motor rated at 5,200 h.p. 750 r.p.m. 0.95 p.f. and supplied at 5,600 volts 3-phase 50 cycles. In addition to the three main machines, this M.G. set also carries the exciter for the synchronous motor and the constant voltage exciter for the control and excitation supply. Reactor starting is used for this set.

In accordance with the Company's normal practice, all machines were designed with a view to the particular duty they had to perform. All were provided with special steelworks insulation, and where it was thought that further strengthening was required in addition to the inherent robustness of construction in standard machines of this type, this was included. As can be seen from Figs. 1 and 2, fabricated construction was largely used in the construction of the machines, including the bedplates.

Forced ventilation was not necessary, and was not used for any of the machines. It was essential, of course, that the motor rooms should be ventilated, in view of the concentration of power within them. The air for this ventilation had moreover to be clean.

The system adopted was to blow clean air into the basement beneath the roughing mill motor room and allow it to pass through the foundation pits of the main machines into the motor rooms. The basements beneath the roughing and finishing mill motor rooms are connected by a large tunnel running beneath the mill, which is used for cables as well as ventilating air. The air is delivered into the roughing mill basement by two axial flow type screw fans, each capable of delivering 50,000 cu. ft/min. Each fan is mounted in a diffusion duct connecting the filter room and the basement, and inclined at an angle of 45°. The rotors are directly driven by 22 h.p. 960 r.p.m. squirrel-cage

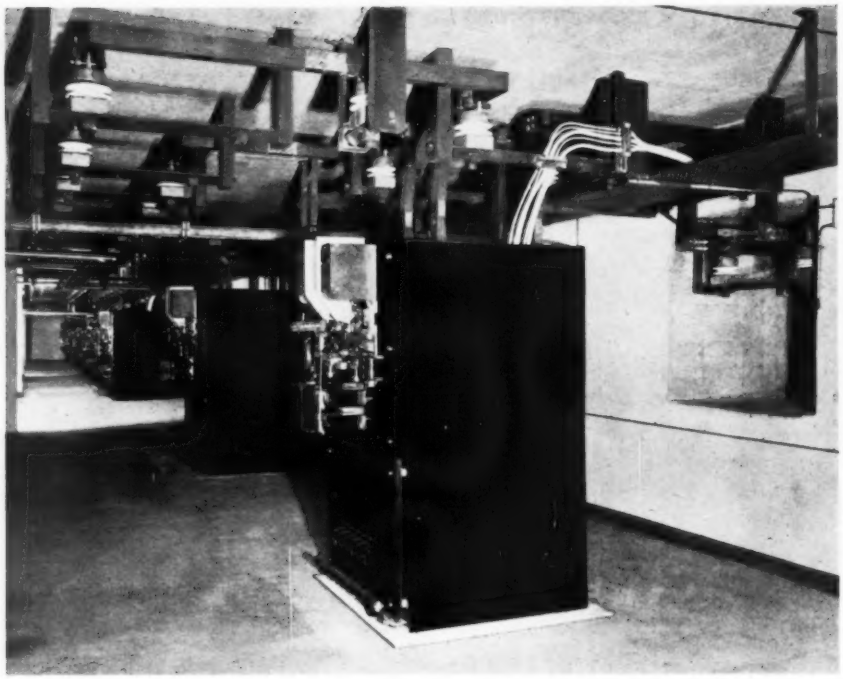


Fig. 3.
Roughing mill basement, showing circuit-breakers for roughing mill motors and generator

induction motors, flange mounted on the upper end of the fan. The fans draw air from separate chambers, the air being drawn into each chamber through four self-cleaning viscous oil type filter units of Visco manufacture.

Main Drives—Control and Operation

Each generator feeds its respective busbars through a double-pole solenoid operated air circuit-breaker. Similarly each main motor is fed from the busbars through a solenoid operated double-pole breaker, and two single-pole contactors are provided in the armature loop of each edger motor and generator. All these units are mounted in the basement, each breaker being situated opposite the foundation pit of its associated motor. This arrangement, shown in Fig. 3, reduces the length of armature connections required and gives a greatly simplified and neat arrangement. Also, of course, less space is required on the motor room floor.

The various relays, instruments, etc., for the motors and generators are mounted on a central control board situated in the roughing mill motor room and shown in Fig. 4. The motorised field rheostats are situated on a gallery running the whole length of the motor room, as can be seen from Fig. 1. The instruments and controls for the mill operators are mounted on a desk in the mill pulpit and, in addition, a control panel is provided at the furnace, on which are duplicated certain of the controls for the first three roughing train drives.

All the main drives are controlled from the one mill pulpit (see Fig. 5) situated on the drive side of the roughing train. From this pulpit the operator controls the circuit-breakers for the generators and main motors as well as the contactors for the edger drives. Indicating lamps are provided to show whether the breakers and contactors are open or closed. The operator also has complete control of the generator voltage and the speeds of the individual motors. Instruments are provided on the desk to indicate the speed and armature current

of each motor and the voltage and armature current of each generator. The speed indicators are each provided with a pointer which the operator can set by hand to mark the set-up speed for the rolling programme.

When starting the mill, the pulpit operator selects the motors which are required by closing the appropriate circuit-breakers. Interlocks prevent any breaker being closed unless the busbar voltage is zero and the field and control circuits for the associated motor are energised. The mill is then started up as a unit by raising the generator volts. When the voltage is set to the desired value the speeds of the individual motors are set, by adjusting their fields, to the values previously calculated to suit the programme to be rolled. Normally, when starting a new programme the mill is run at a reduced voltage for the first few billets, any adjustments necessary being made before the mill is speeded up. The mill can be started and stopped with the motor field rheostats in any position.

The voltage of each generator is controlled by a motorised potentiometer rheostat which varies the voltage across the generator field. This rheostat is arranged as a reversing potentiometer so that the mill can be reversed in an emergency if required. A separate control switch is provided for selecting forward or reverse running. A second motorised rheostat is connected in series with the generator field to give a fine, or vernier, control of the generator voltage. Also connected in series with the field is an automatic voltage regulator which maintains the generator voltage constant at the value chosen.

For controlling the speeds of the individual motors, by varying their fields, two rheostats are connected in series with each motor field. One is designed to give coarse control and the other to give vernier control. In the case of the roughing and intermediate stand motors, both these rheostats are motorised. The vernier rheostats for the five finishing train motors are, however, hand operated by means of a vertical lever on the pulpit

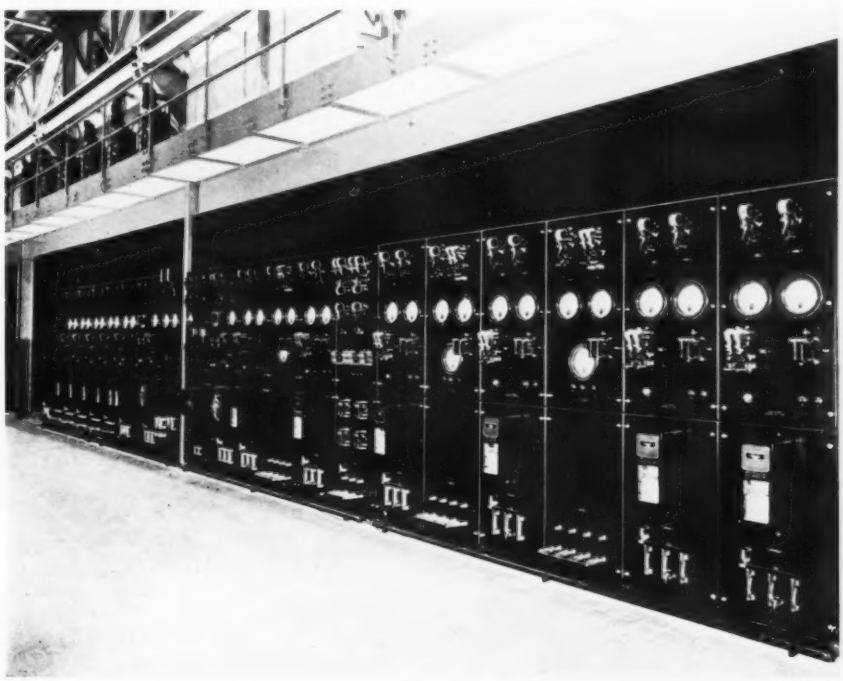


Fig. 4.
Central control board for all main drives

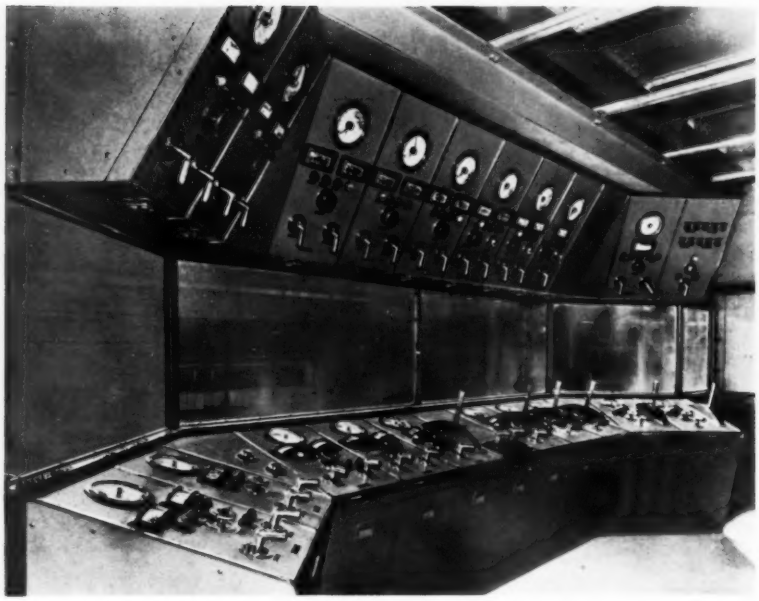


Fig. 5. Main mill control pulpit with controls on upper part of desk for certain roughing train motors, the main generators, variable-frequency run-out tables and vibrator, and on the lower part for the other roughing train motors and the intermediate and finishing train motors

desk. The rheostats themselves are mounted beneath the pulpit and are accessible from the motor room.

In continuous mills of this type the piece can be in a number of, or in fact in all, stands at once. It is essential, therefore, for satisfactory rolling that the variation in motor speed between full load and light load, i.e., the speed regulation of the motors, shall be low. One reason for this can be seen by considering, for example, a piece which is just about to enter No. 3 stand. As the previous piece will by then have left No. 3 stand, this stand will be running at its light load speed. The previous stands will, however, be running at their full load speed and hence stand No. 3 will be running faster than the speed corresponding to that of the approaching piece. It will actually have been adjusted so that when rolling the particular programme concerned its speed on load will be correct. Thus it will be seen that each stand will tend to snatch the nose of the piece, and the greater the difference between light load and full load speeds the greater will be the snatching effect.

The speed regulation of a motor can be reduced either inherently in the motor design (i.e., by making the motor large for its output) or by providing special control features. For this equipment it was decided that a maximum regulation of 2 per cent. would be acceptable, and that the motors could be designed to give this inherently while still remaining reasonable from both the economic and design points of view. This alternative was therefore chosen in preference to special control features. It was considerably simpler and, in addition, the larger motors with low inherent regulation have the advantage of a lesser speed drop on impact than could be achieved otherwise. The excellent results obtained on this mill have justified this choice.

Speed variations due to varying loads on the generators are prevented by the action of the automatic voltage regulators. An automatic voltage regulator is also provided for the constant voltage exciter which supplies the field and control circuits.

An emergency stop button is provided by means of which the whole mill can be stopped by reducing the generator voltage. In addition, dynamic braking is provided for each motor, should it be required to stop any one individually.

Originally, special provision was made to maintain the ratio of speeds of the last two roughing

stands exactly constant under all conditions. This was done by comparing the speed of each motor with that of a small D.C. control motor, through variable speed and differential gears. Any difference in speed, between either of the motors and the control motor, operated a carbon pile regulator through the respective differential gear. This regulator in turn acted through a booster exciter to vary the main motor field so as to maintain the correct ratio of speeds. The ratio of speeds could be adjusted by means of the two sets of variable speed gears, and the value of speed varied by varying the speed of the D.C. control motor. Operational experience on the mill, however, showed that excellent results were obtained even without using the special control of ratio of speeds on the last two roughing stands. Consequently this equipment has now been disconnected.

As the pulpit operator cannot closely observe conditions at the first roughing stands, a control panel is provided at the furnace, as previously mentioned. This panel is equipped with speed controls, speed indicators and ammeters for the first three stands, to duplicate those on the pulpit. The operator on the mill floor can therefore control these stands according to the rolling conditions, which he can readily observe. This panel also carries ammeters indicating the load on certain other main drives.

Edger Control

It is desirable that the speed of the edger rolls should match the speed of the rolls in the preceding stand. As already mentioned, this is obtained by feeding each edger motor from a generator coupled to the motor driving the preceding stand. The voltage of this generator is proportional to its speed, and hence the speed of the edger motor is proportional to the speed of the preceding main motor. Motorised rheostats, operated from the pulpit, are provided in the fields of edger motors and generators for adjusting the speeds of the edgers relative to the preceding main stands. One of these rheostats combines the generator control and the coarse motor field control, the motor field control following on after full generator volts have been reached. The other rheostat provides vernier control of the generator field. The edgers are started after the remainder of the mill has been run up, using their own rheostats.

Auxiliary Drives

The majority of the mill auxiliaries are driven by D.C. mill motors of the ' English Electric '

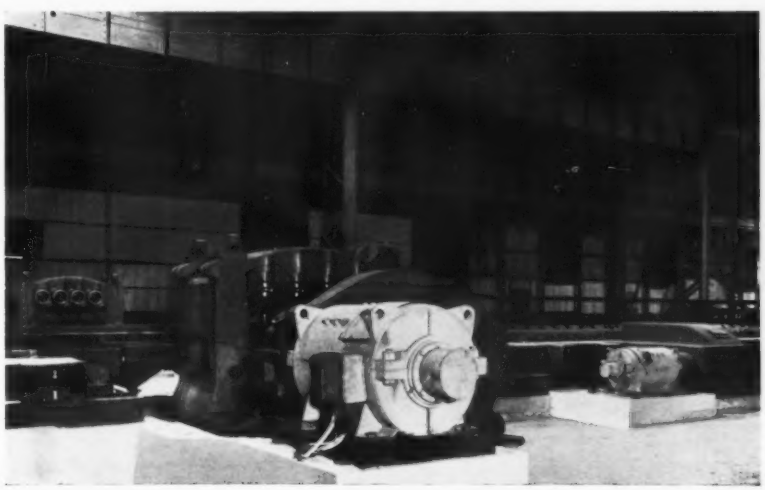


Fig. 6. Outgoing side of cooling bed, showing the two roller straighteners driven by CMR type mill motors and the drive for one of the cooling bed run-out tables

CMR type. Two of these can be seen in Fig. 6 driving one of two roller straighteners and one of the cooling bed run-out tables. These motors are of very robust construction, have low inertia, and conform in dimensions to the standard laid down by the American Iron & Steel Engineers, which standard has also been adopted on a large scale in Great Britain.

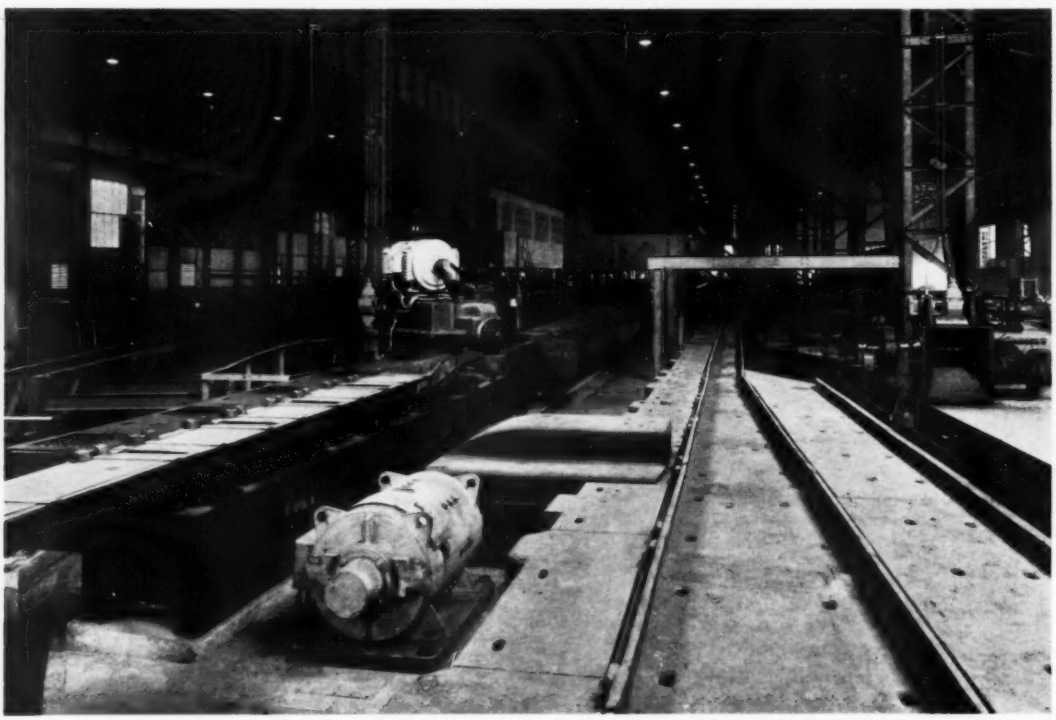
Certain drives which are continuously running are driven by A.C. motors or, where a variable speed is required, by D.C. industrial type motors. An example of the latter is seen in Fig. 7 which shows the rotary shear driven by a 15 h.p. 400/1,600 r.p.m. louvre ventilated CAM type D.C. motor.

The drives for the run-in tables to the cooling bed are also of interest. Here it was necessary to keep to the minimum the space occupied by the drive for each roller. The rollers for the two tables were therefore overhung on opposite ends of each roller motor shaft. To take the weight of these rollers the motors were made with special cast steel frames, and the construction adopted can be seen in Fig. 8.

Normal contactor control panels, with inductive time limit control of the accelerating contactors, were adopted for the majority of the drives. This portion of the control gear was sub-contracted by The English Electric Company to the Igranic Electric Company. One of the contactor boards for the roughing mill is shown in Fig. 9 and a contactor house for the finishing mill in Fig. 10.

Special control features were, however, adopted for the vibrator and for the run-out tables to the cooling bed. As already mentioned, the vibrator is used when coiling strip. It comprises, essentially, a pair of small vertical rolls which oscillate in the horizontal plane at right angles to the flow of the strip. Immediately beyond the vibrator is a slowly moving slat table. Under the combined action of the vibrator and this moving table the

Fig. 7. Entry side of cooling bed with run-out table from finishing train on left together with rotary flying shear. On the right is the skew-Y table, with driving motor, which transfers the bars from the roughing train to the intermediate stand



strip is snaked on edge and remains on edge due to its formation (Fig. 11). As it leaves the other end of the table the strip is fed to the vertical coiler. In addition to maintaining the strip on edge, the snaked formation also provides a reservoir of strip from which the coiler is fed, so that the latter need not be accurately synchronised with the mill.

It is desirable, however, to synchronise the oscillations of the vibrator with the strip speed. To this end the vibrator motor is supplied from a variable-voltage generator which is excited from a pilot exciter driven by the stand from which the piece leaves the mill. The generator has a straight-line open circuit characteristic (i.e., its field is unsaturated over the working range) so that its output voltage is always proportional to its excitation and hence to the pilot exciter voltage and the speed of the last stand. Since the piece may leave the mill from any of the finishing stands, a pilot exciter is mounted on the end of each of the motors driving these stands. A selector switch is provided for connecting the vibrator generator field to the appropriate exciter. The M.G. set for the vibrator can be seen against the rear wall of the finishing mill motor room in Fig. 12.

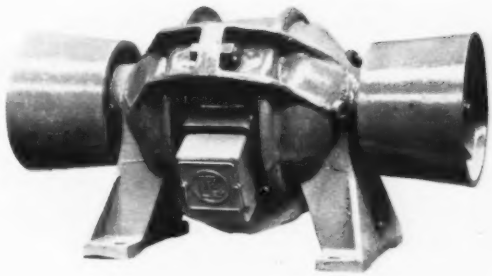


Fig. 8. One of the specially built squirrel-cage motors for driving the mill run-out tables. These motors are totally enclosed and have special cast steel frames to carry the weight of the table rollers mounted on each end of the shaft

The length of the cooling bed run-in tables and the spacing of the rollers made it desirable, as is usual for such tables, to drive each roller individually rather than to attempt group driving through bevel gear trains. Squirrel-cage induction motors were chosen in preference to D.C. motors for driving the rollers, as such a large number of D.C.

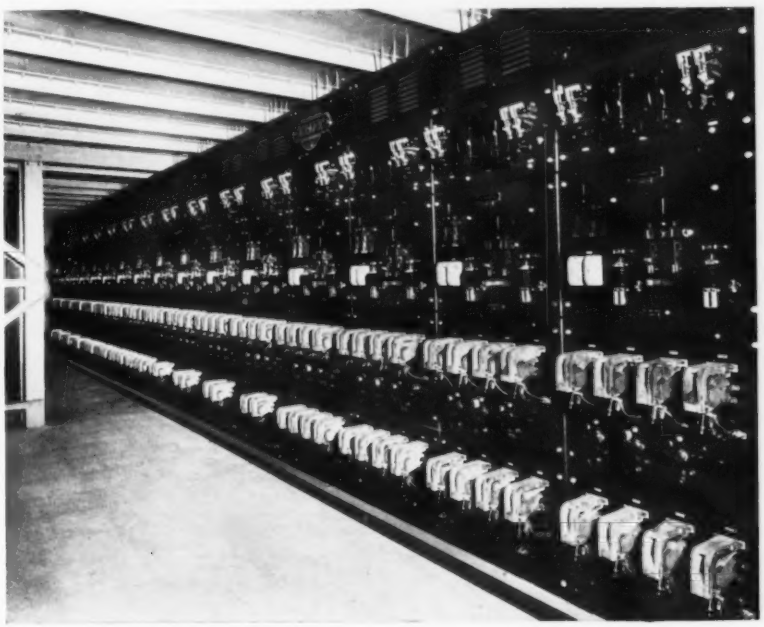


Fig. 9. Contactor board for D.C. constant voltage auxiliaries at roughing end of mill

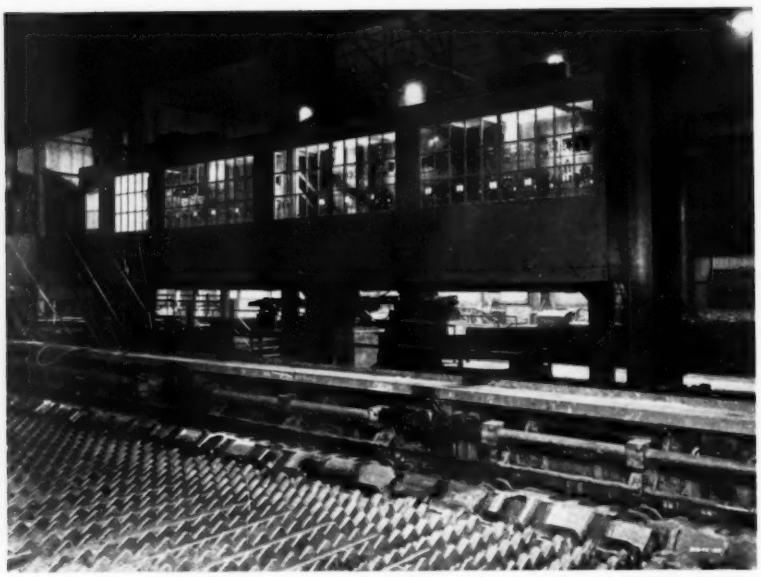


Fig. 10. *Contactor house at the cooling bed*

motors with their commutators in a not very accessible position would be expensive in first cost and also to maintain. To enable the table speed to be varied to suit the piece speed, these roller motors are fed from a variable-frequency alternator set. The speed of the driving motor for this set can be varied by means of a field rheostat situated in the main pulpit. Further, the armature of this motor is supplied from the finishing mill busbars so that any variation in busbar volts automatically varies the run-in table speed approximately in proportion to the resulting change in mill speed. The motor-alternator set can be seen in Fig. 12, with the alternor exciter set at the left.

The roller motors are arranged in five interlocated groups. Thus the first group contains motors Nos. 1, 6, 11, etc., the second group contains motors Nos. 2, 7, 12, etc., and so on. All motors in each group are fed from the same three-phase busbars, but each motor has its own contactor. These contactors are each mounted in a cast iron box, together with a thermal overload relay to give individual protection, and the units are situated in groups beneath the motors in the cooling bed basement. The motors are direct-on-line started using their own contactors, which are in turn controlled by 5 group contactors. These group contactors are controlled by a timing relay to close in sequence, so as to reduce the load on the alternator during starting. Since even with sequence starting the peak on the alternator is still rather heavy, field forcing is provided during starting.

Power Distribution Equipment

The electric power supply to the mill is brought in through two feeders at 5,600 volts. These feed a 15-panel cubicle type switchboard housing 'English Electric' type OLD circuit-breakers (Fig. 13). This board is divided by bus-couplers into three sections. The centre section feeds the main M.G. set and one of the 440 volt transformers, and also has a spare breaker. Each outer section feeds one 440 volt transformer and one rotary convertor. Thus either end of the board can be isolated without necessitating a mill shutdown. The feeders mentioned do not total 15, but this number of panels includes voltage transformers, a reactor shorting breaker and the spare feeder. All the breakers are hand operated except the main breaker and reactor switch for the synchronous motor. These are solenoid operated

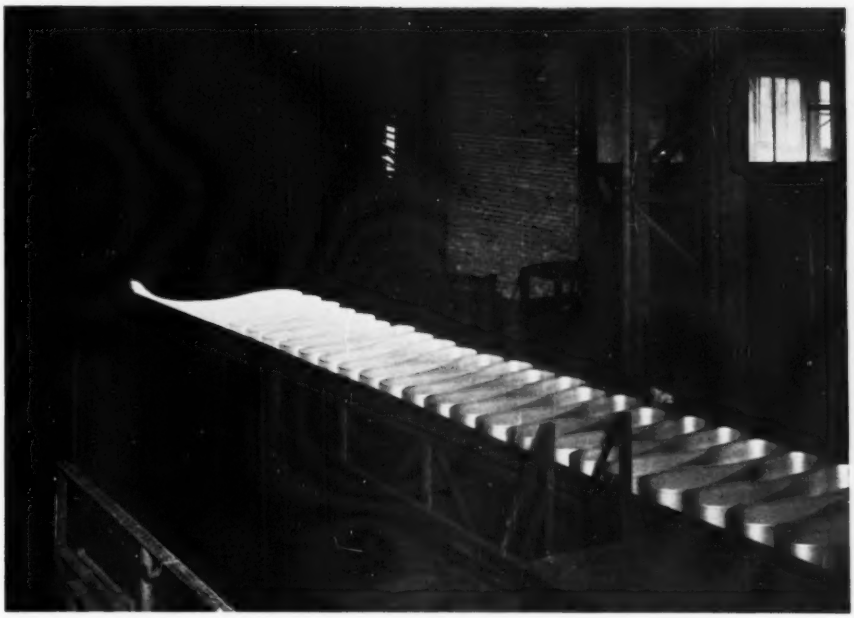


Fig. 11. *Strip on moving slat table after being snaked on edge by vibrator. At the far end the tail can be seen, having just left the vibrator rolls*

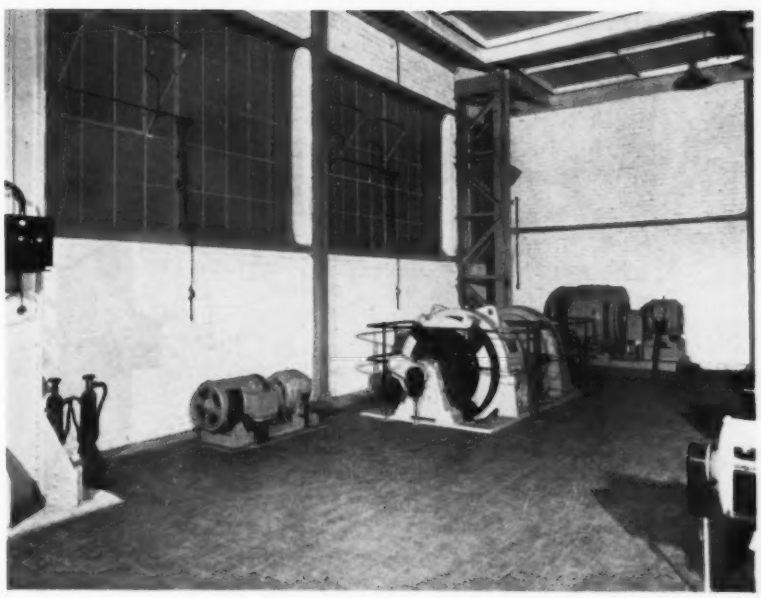


Fig. 12. *Finishing mill motor room, showing the variable-frequency alternator set with its exciter set on left. The M.G. set for the vibrator is against the rear wall*

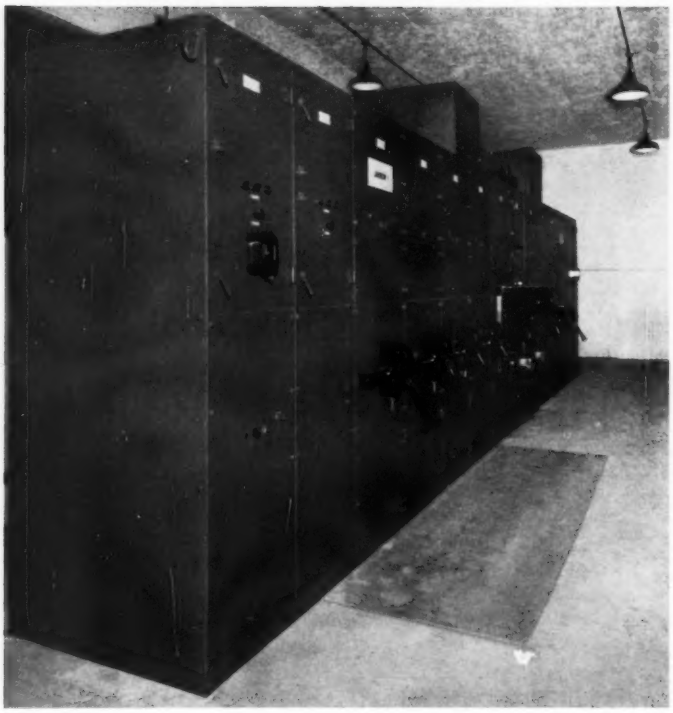


Fig. 13. *The* 15*-panel* 5,500 *volt distribution board equipped with OLD type oil circuit-breakers. The two solenoid operated breakers in the centre are for the stator of the main M.G. set and for shorting its starting reactor, respectively*

since the motor is provided with automatic starting controlled from the motor room.

The supply for the A.C. auxiliaries such as fans, exciter sets, pumps, etc., is 440 volts 3-phase 50 cycles. This is obtained from three 400 kVA 5,500/440 volt transformers through a 440 volt distribution board.

The D.C. auxiliary drives are fed from a 480/240 volt three-wire system supplied from two 700 kW rotary convertors.

Conclusion

The mill has now been operating very successfully for 11 years and very little trouble, and certainly no major trouble, has been experienced from either the mill itself or the electrical equipment. Typical production figures are :—

Year	Total working hours	Annual tons output
1942 ..	2,696	54,604
1943 ..	2,262	44,903
1944 ..	2,377	59,442
1945 ..	2,260	50,569
1946 ..	4,251	82,095
1947 ..	3,951	99,604
1948 ..	4,504	125,463
1949 ..	4,693	132,382
1950 ..	5,897	142,169

The figures given for total working hours include meal times, roll changes, etc. The total hours during which rolling was carried out were of course appreciably less. As an example, the total hours actually rolling for 1949 and 1950 were 3,686 and 4,263 respectively.

The record weekly and shift outputs in tons, are :—

	Shift	Weekly
Angles ..	320	3,351
Flats ..	418	4,046
Strip ..	335	4,232

Stoppages due to electrical faults have been very few, the longest total time for stoppages in any year due to electrical faults being only 0.419 per cent. of the total working hours. The minimum was in 1944 when the total time for electrical stoppages was only 0.126 per cent. of the total working hours.

The consumption of electrical energy varies, of course, according to the product being rolled. Taking an average for all products rolled from 1942 to 1948 inclusive, the total consumption for all services, including cranes, machine shop, lighting and heating, was 66 units per ton.

Finally, we wish to acknowledge the kindness of the Consett Iron Company Limited in permitting the publication of this description and in supplying much of the information regarding the operation of the mill.

10 kV D.C. Electronic Insulation Tester

By L. R. HULLS, B.Sc., A.Inst.P., Industrial Electronics Department, and
J. WAINWRIGHT, A.M.I.E.E., Grad.I.Mech.E., Assoc.A.I.E.E., Insulation Engineering Department.

THIS INSTRUMENT HAS BEEN designed to meet the need for a reliable, simple and portable equipment for determining the performance of insulating materials under high voltage stress. The apparatus gives an output voltage continuously variable from 500 to 10,000 volts D.C., a means for measuring resistance values up to 250,000 megohms, and an aural indication of the A.C. component of leakage or ionization current through the test specimen.

For the purpose of description, the design may be considered to consist of three units ; (*a*) high voltage power-pack ; (*b*) measuring unit ; and (*c*) ionization amplifier. A description of these units (Fig. 1) and of the advantages of the design gives some indication of the capabilities of the apparatus.

The High Voltage Power Pack

This unit comprises a 6V6 output tetrode working as a 100 kc/s oscillator. The output from the oscillator is by way of a step-up air cored transformer " T " which gives the necessary D.C. output voltage after half wave rectification and smoothing. Variation of the output voltage is achieved by adjusting a potentiometer " P " controlling the screen potential of the oscillator valve.

This design of power unit offers considerable advantages over the more conventional rectified 50 c/s unit. The most important advantage, when considering a portable unit, is the reduction in weight and size. The air cored transformer is small and simple in design, and the use of a comparatively high frequency makes possible efficient smoothing with only small values of capacity. Another important feature of the design is the reduction of stray leakages which result when an air cored transformer is used, as these leakages are capable of causing considerable errors when measuring small currents in the test specimen.

The power pack has been designed to deliver a maximum current in the region of 0·5 milliamp and, therefore, there is no necessity for special safety precautions when using the instrument as the high voltage supply cannot give a fatal electric shock.

The Measuring Unit

The measurement of current and voltage is achieved by a valve bridge circuit feeding a 1 milliamp meter " M." Current measurements are made by measuring the voltage developed across a standard resistance R_3, R_4, R_5, placed in series with the test specimen, and voltage measurement by measuring the voltage from a potential divider " D," connected across the test supply.

The voltage to be measured is applied to the grid of a high slope pentode which is connected as a cathode follower in one arm of a resistance bridge. The output from the bridge feeds the indicating meter.

A selector switch " S.1 " is provided to switch the bridge input to either a standard series resistance or the potential divider to give current and voltage measurements respectively A further switch " S.2 " selects one of three values of standard high stability resistance, to give three current ranges. A set zero control " R.2 " is provided to enable the initial bridge balance to be made and an internal pre-set resistance " R.1 " ensures that the correct relation between bridge input voltage and meter reading can be obtained.

The bridge circuit was found to give good stability with mains supply variation, and although the valve introduces a slight non-linearity, the

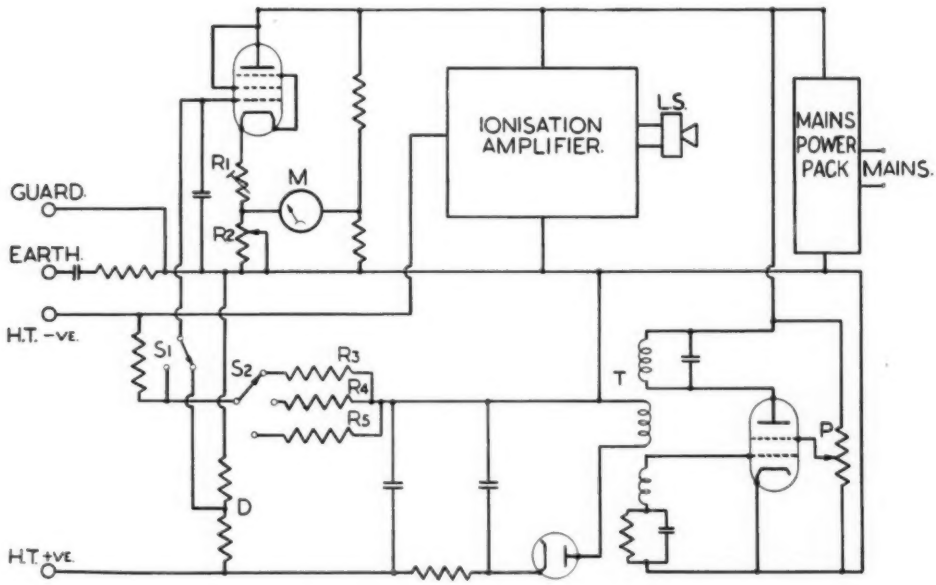


Fig. 1. Schematic circuit diagram illustrating the general arrangement of the high voltage power-pack, measuring unit and ionization amplifier

overall accuracy, when calculating resistance from current and voltage measurements, is within 10 per cent. for resistances up to 2,500 megohms and within 20 per cent. for resistances up to 100,000 megohms. It will be noted that after making the initial zero balance, the circuit gives direct reading of current and voltage.

The application of electronic methods to this unit has two advantages. Firstly, it enables the use of a reasonably robust meter, and secondly, it enables extremely small currents outside the range of most sensitive meters to be measured.

The Ionization Amplifier

This unit consists of a small two stage audio amplifier feeding a midget loudspeaker "L.S." The input to the amplifier is derived from the A.C. component of the current passing through the test specimen. The circuit gives the operator an audible indication of the degree of ionization in the test specimen and an early warning of impending breakdown.

Considerations in Design

Although the equipment comprises units designed in accordance with established electronic technique, considerable experimental work has been necessary in order to combine these units into an equipment which will accurately measure the high resistances encountered in insulation testing. In order to obtain the desired result a somewhat unusual form of construction has been adopted in which all the sub-assembly chassis of the various units are mounted direct on to a front panel of insulating material. This isolates the electronic equipment from the case which is at earth potential, as is necessary if the test set is to give a reading which is independent of any earthing of one side of the test specimen.

The mechanical layout takes full advantage of the insulated front panel construction, and as far as possible each electrical unit has been kept as a separate sub-assembly mounted independently on the front panel. This procedure is of advantage both in the production and servicing of the test set.

The most difficult problem encountered during the design was the elimination of stray leakages, and it was found that leakages which would normally be disregarded in electronic equipment were sufficient to upset the measurement of small currents. It will readily be appreciated that in equipment measuring resistances of 250,000 megohms an unwanted leakage path of this order of resistance is capable of causing measurement errors in the region of 50 per cent.

Generally, it was found necessary to guard carefully all the points where leakage was likely to take place. The diagram shown in Fig. 2 illustrates the method of operation of the guard system used. It will be seen from the diagram that any current flowing from the +ve side of the source to the guard connection by-passes the measuring unit and is, therefore, not recorded on the indicating meter. In actual practice all the subassembly chassis are used as guards, being connected to the supply side of the measuring unit. It is this feature which necessitates isolating the chassis from the earthed case as the test set is often used with the negative potential side earthed.

Any leakages between guard and the earthed case, when the H.T.-ve side is earthed, shunt the measuring resistance R_3, R_4, R_5, and careful design of the front panel has been necessary to ensure that any leakage resistance between chassis and case is large in comparison with the highest value of measuring resistance.

The mains supply transformer is also a potential source of error as any leakage from the high voltage rectifier heater winding through mains input winding back to earth, may eventually appear as a potential drop across the current measuring resistor. Electrostatic screening of the appropriate windings on the mains transformer overcomes any leakage difficulties at this point.

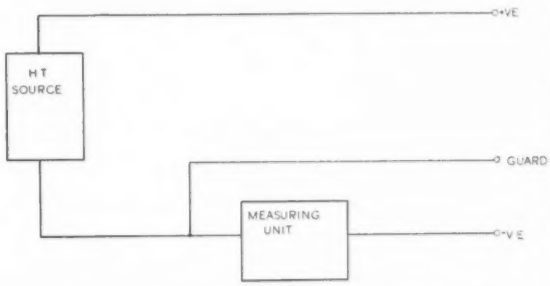


Fig. 2. Schematic diagram showing method of operation of the guard system

Choice of materials for insulating components is a very important aspect of the design of such an equipment and it is interesting to note that the best method found for testing the insulating material was by using the original laboratory model of the test set.

The instrument is contained in a case measuring 15 in. × 10½ in. × 6 in. and weighs 23 lb. The illustration, Fig. 3, gives an indication of appearance and layout of the tester.

Fig. 3. 10 kV D.C. Electronic Insulation Tester

Insulation Resistance Measurement

In order to appreciate the facilities provided by the new test set it is necessary to consider its performance in relation to other methods used for insulation resistance measurement.

Although the exact interpretation of the insulation resistance of a piece of apparatus, or a component, may be difficult, there is no doubt that a knowledge of its value can give a very useful indication of the condition of electrical insulation. For example, although the test will not always discriminate between reduced volume resistivity, say, due to moisture absorption by a hygroscopic material, and reduced surface resistivity due to a deposit of dirt on a leakage surface, it will indicate that all is not well with the apparatus as a whole.

Periodic testing with an instrument that measures insulation resistance is, therefore, of first-rate importance, and it is true to say that a large number of plant failures have been averted by this means.

As most insulation resistances are voltage-dependent, it is a definite advantage to take readings at a voltage of a similar order to the operating voltage, so that the actual value under working conditions will be known. In many cases it is impracticable to take measurements at the peak working voltage, but the provision of a high test voltage makes it possible to obtain insulation resistance values which would be outside the range of an equipment with a lower test voltage.

In the laboratory, when a high degree of accuracy is required, it is usual to use a battery of cells (thereby ensuring a constant voltage) and to measure the voltage and current simultaneously. For higher voltages one of the recognised methods employing transformers and rectifiers or voltage multiplying circuits may be used. The test voltage will be measured by a high resistance voltmeter and the current by a sensitive galvanometer with a universal shunt. This method of measurement has the great disadvantage that the galvanometer is a very delicate laboratory instrument and totally unsuitable for the usual onerous conditions encountered by portable testing equipment. In particular, a failure of the insulation during testing or an inadvertent short circuit of the test leads will almost certainly result in the galvanometer burning out.

For general works testing, including factory maintenance, there is no doubt that a test set employing a self-contained, hand-driven generator is well established and for many uses seems likely to remain so. The main advantages of this method are that the test set is completely independent of external supplies (excluding man-power) and that the scale is calibrated directly in megohms.

The chief disadvantages of the test set with a self-contained generator are that the charging current-time curve at a given applied D.C. voltage is exponential in form and with comparatively clean dry insulation the time for the rate of change of current to become small may be of the order of 5-10 minutes. To attempt to turn the generator handle of a test set for times of this order is a physical impossibility and, with large capacitance, variations in the speed of turning the generator result in alternating charge and discharge currents with a consequent fluctuation of the pointer. In certain cases these fluctuations may be so great that it is impossible to make a useful estimate of the value of the insulation resistance being measured.

These disadvantages have been overcome in such test sets by the use of mains motor drives, but the size and weight are increased considerably and the sets are no longer entirely self-contained.

A third method of measuring insulation resistance generally consists of a source of high voltage obtained from a 240 volt A.C. supply, and electronic means of measuring current and possibly voltage. As in the case of the galvanometer method the insulation resistance is obtained by dividing the voltage by the current. The new insulation test set is in this class.

From the technical data given it will be obvious that the new instrument overcomes most of the disadvantages of the other methods referred to. The size and weight are exceptionally small, the set is extremely robust, and there is no possibility of damage due to mishandling. The high output voltage makes it possible to take readings at the peak value of the working voltage on plant up to 11 kV three-phase, and also in the special case of certain 33 kV alternators.

The insulation resistances which can be measured are ample for all work in the field and for most work in the laboratory. The maximum is some five times greater than can be obtained at present with test sets using a self-contained generator.

The new test set can be used with the advantages mentioned in most of the places where existing insulation resistance test sets are used. One interesting application is the testing of insulating oils in the field, from transformers, switchgear, etc. It has recently been suggested* that the insulating quality of oil can be assessed by means of an insulation resistance test. The new test set is ideal for this purpose. Other applications are tests on rotating machines, transformers, cables and switchgear of all voltages and ratings both

* Forrest, J.I.E.E., vol. 95, part II, No. 45, p. 337.

during works processing and after installation in the field. The fact that the low voltage side of the test set can be connected to, or isolated from, earth is a useful feature where installed apparatus is concerned. The provision of a " guard " terminal makes possible the use of a Price guard system so that surface leakage effects can be eliminated.

The Ionization Detector

If, as already stated, it is difficult to assess the real meaning of insulation resistance, it is perhaps true to say that with our present knowledge the true interpretation of ionization is impossible. In spite of this somewhat theoretical difficulty, however, an ionization detector can be of practical use. For example, in the manufacture of components, particularly condensers, it is possible to reject individual items on a purely comparative basis. Any component which is obviously " noisy " compared with the remainder of a particular batch, can be put on one side for further investigation.

It will be many years before safe limits can be allowed for any particular apparatus or component and in the meantime a certain amount of caution will be needed if wrong decisions are to be avoided.